DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH

SCIENCE AT WAR

by

J. G. CROWTHER

AND

R. WHIDDINGTON, C.B.E., F.R.S.

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FOREWORD

By Sir Henry Dale, O.M., G.B.E., F.R.S., *Chairman of the Scientific Advisory Committee to the Cabinet*

PERHAPS the most suitable introduction that I can write for " Science at War " is to say something about its origin and purpose.

It has sometimes been suggested that the recent war was won by the scientists, but I do not remember hearing any scientist make such a claim. Like all earlier wars, it was fought and won by the men in the Forces. The scientists, like the rest of the nation, served the fighting men to the best of their ability, and not without some share even in the perils to life and limb. It is undoubtedly true, however, that science played a much larger part than in any earlier war, and the fact that scientists of the Allied Nations were able to overtake those working for the enemy, and then to keep ahead of them, played a very important part in our ultimate victory.

During the war our scientists had for obvious reasons to do much of their work under the veil of secrecy. As a result, many of their achievements are either unknown as yet to the public, or known only through partial and inaccurate descriptions which, if they are not corrected quickly, may harden into traditions which will hand on to the future a misleading account of what was accomplished. Such considerations led the Scientific Advisory Committee to the Cabinet to obtain the approval of the Government for the preparation of this work. Our object was to make available to the public an authoritative account of some of the more important aspects of the scientific contribution to the war effort, based on the official archives, but so written as to be acceptable to the reader without special scientific education. The reader must judge for himself the extent to which we have realized this intention. I am convinced that we were fortunate in securing the services of Mr. J. G. Crowther and Professor R. Whiddington, C.B.E., F.R.S., to carry out the task for us.

I should, perhaps, give some idea of the way in which the work was planned and written. It was early clear to the Scientific Advisory Committee that it would not be possible for the authors to cover the whole field of the scientific war effort ; the account of it must therefore be illustrative rather than comprehensive. We were also convinced that our object would best be served if the authors were able to exercise a wide discretion as to its form and contents. The Government departments, from which the material of the story has been drawn, must clearly have an opportunity of commenting

on the separate sections of the work, and of offering criticism while it was still in draft. The whole book had, further, to be carefully examined from the point of view of security by those responsible to the Government for such matters. Mr. Crowther and Professor Whiddington were told, however, that, in writing their account, they must regard themselves as free to use their own discretion as to the treatment of the material placed at their disposal, and that, while the Committee would expect them to give the most respectful attention to criticisms received from Government departments, they should not regard these as overriding their own judgment as to the choice of matter for description and the appropriate manner of its presentation. The responsibility for the book which is now offered to the public must be taken, therefore, by the Scientific Advisory Committee, and by the two authors commissioned to write it on our behalf.

The responsibility is one which the Committee most gladly accept. They believe that a large section of the reading public in this country will welcome such an authoritative, though technically simple, account of the part played by British scientists in dealing with some of the endless succession and variety of scientific problems, which the war presented with such urgency for solution. The chapters here offered should enable the reader not only to understand the nature of the problems chosen for description and the scientific principles invoked to deal with them, but also to form some idea of the high qualities of mind devoted to the work and the spirit of enthusiasm and comradeship, which enabled the required results to be obtained with the speed which is one of the principal factors of success in war. The whole achievement, which these chapters illustrate by chosen examples, is one of which British science and the British nation have good reason to be proud.

There will be no thinking man, however, among the readers of this book who, with a proper pride in its record of what has been done, will not cherish a most earnest hope that the call for such sacrifice will never come again. The use of science as an aid to war is a perversion from its proper purposes, and its rapidly extending misuse in the recent war, as a direct agent of violence and destruction on a stupendous scale, creates a threat to the survival of civilization. Meanwhile we may find some reassurance in recognizing that much of the discovery and invention which came so rapidly to hand, in response to the tremendous stimulus of the recent war's demands, will find immediate and beneficent uses in peace.

I

RADAR

ALMOST AS soon as radio was invented, methods were devised for discovering the place of origin of radio signals. Such methods were necessary in order to use radio for finding the exact position of ships in distress at sea, and for other applications. It was possible to discover the origin of the radio signals by finding the direction from which they were coming.

But this was not radiolocation. The radiolocation of an aeroplane does not in general depend on waves originating from the aeroplane.

Radiolocation depends on the reflection of radio waves from objects. It enables the place of an aeroplane or a ship to be detected, merely by reflection of radio waves, just as their places might be revealed in the dark by floodlighting, or by the beam of a searchlight. Radiolocation is, among other things, an extension of seeing. An aeroplane can be radiolocated merely through being there. Radio silence, darkness, fog will not prevent the aeroplane from being located.

Radiolocation is similar in principle to the discovery of obstructions in the dark by shouting or clapping. If you are lost on a dark night in rocky country, you may be able to obtain some idea of the position of neighbouring cliffs by clapping your hands, and noting the direction from which the echo returns, and the time it takes. As the velocity of sound is known, it is easy to calculate the distance of the cliffs from the time taken by the sound to travel to and from them.

The first fundamental physical principle in radiolocation is the use of the radio reflection, the echo of radio waves from an object against which they have been projected. The second physical principle is the measurement of the time taken by the echo to travel from the reflecting object to the observer who is watching for it.

These two principles were first used in combination by Professor E. V. (now Sir Edward) Appleton, in 1924, for the measurement of the height of the ' Heaviside layer.' The existence of a conducting

layer in the upper atmosphere had been inferred (by Balfour Stewart, Heaviside and Kennelly) from theoretical considerations. The discovery that radio waves, which travel in approximately straight lines, could go round the bend of the earth's surface, had been a notable practical surprise. It was suggested that the waves got round the bend through being reflected by the layer. Thus the existence of the layer became a question of fundamental scientific importance. The indirect evidence for it was strong, but direct proof was desirable. The best way of obtaining this was by measuring its distance from the surface of the earth. Appleton sent radio waves up to the layer, and detected them on return after reflection. He measured the time taken by the waves on their journey, and calculated from this that the layer must exist at the height of about 60 miles.

Utilization of the radio echo method for the location of aeroplanes, and its utilization as a military weapon, involved a mighty effort of applied science in which the chief leader in the United Kingdom has been Sir Robert A. Watson Watt. This great development of technique has latterly been given the comprehensive name of RADAR, which ingeniously suggests the echo principle, for the same word is spelled whether read forwards or backwards. Radar, however, includes many important innovations, such as certain radio navigational aids, which do not utilize radio echoes.

All developments in science follow from what has already been discovered. The existence of radio waves was first proved by Hertz in experiments which were remarkably simple and beautiful. He showed that the oscillations of electricity in the spark from an induction coil produce waves that travel with the speed of light, and, like light, have the properties of reflection, interference, refraction and polarization. He noticed in his earliest experiments the influence of walls on the path of the waves. He recorded how two rows of iron pillars in his lecture room acted as reflecting walls, and tended to confine the waves to the space between them, and he increased the reflectivity of the end wall of the room by fixing a sheet of zinc to it. Hertz subsequently used big concave mirrors for focussing the waves, and prisms made of pitch for refracting them. Thus the earliest radio experiments demonstrated that walls and metal sheets could reveal their existence by reflecting radio waves.

The successors of Hertz soon succeeded in receiving radio waves from distant stations, and the problem of locating the origin of signals arose—for instance, from distressed ships at sea. This depended on determining the direction of maximum intensity of the waves at two stations at the two ends of a base line.

The development of radio communication inspired fundamental

research on every aspect of radio physics. In Britain, the Radio Research Board was formed, in 1920, by the Department of Scientific and Industrial Research, for this purpose, under Admiral Sir Henry Jackson.

The Radio Research Board organized as part of its programme a systematic study of the way in which radio waves travel round the earth. When Appleton in 1924 suggested his method of proving the existence of the Heaviside layer by determining its height he asked the Radio Research Board for facilities to make the experiments. The facilities were given, and he swiftly achieved complete success.

In his original experiments Appleton marked the transmitter wave, by wobbling the wavelength. Thus, when it returned, it was slightly out of phase with the new wave being emitted, so that beats were produced. From the period of these, the time of travel to the layer and back could easily be calculated, and the height of reflection determined. So, already in 1924, the height of a conductor in the sky had been determined by a signal sent from, and received on, the ground. And this conductor, the Heaviside layer, was found to be no less than 60 miles up in the sky. So conductors even so far away could be detected, and their distance measured, by probing radio waves.

Appleton and his associates also developed the pulse method of Breit and Tuve (described later) for measuring the distance of a reflecting surface by radio, the echo's time of travel being measured directly on a cathode ray tube.

But these were scientific experiments, carried out to advance man's knowledge of the world about him. We shall see how they were put to practical development and use when danger threatened.

When that threat came, Britain was fortunate in two things. The purely scientific basis of radar was there. It was also applied in time.

Alarm

After their acquisition of power in Germany in 1933 the Nazis began the construction of a huge air force as part of their aggressive programme. This force was poised menacingly, and Britain was within easy range. The Air Ministry anxiously considered whether any new ways of meeting the threat could be found. The multiplication of existing weapons was not enough, for the prospective enemy had a preponderance of industrial productive power. Could

science provide something new, that would offset the aggressors' numerical advantages and give protection to the great cities of Britain where the bulk of the population lives and the materials of life and war must be made ?

Dr. H. E. Wimperis, then the Director of Scientific Research at the Air Ministry, and his scientific colleague Mr. A. P. Rowe reviewed during the middle months of 1934 the ways in which science might be used for this purpose. It appeared that the problem needed investigation from a completely new point of view. So, in October of that year, Wimperis proposed that a Committee of Research on Air Defence should be appointed under the chairmanship of Mr. H. T (now Sir Henry) Tizard. Other original members were Professor P. M. S. Blackett and Professor A. V. Hill ; Rowe was Secretary.

The situation was grave and the public had already begun to long for death-rays that would dispatch the strongest enemy at will, and the desire had been canvassed in the press.

In January, 1935, Wimperis consulted Watson Watt, then the Superintendent of the Radio Department of the National Physical Laboratory—informally, since the matter was very secret. Within two weeks Watson Watt, with the collaboration of Mr. A. F. Wilkins, one of his colleagues in the Radio Department, produced a note containing an estimate of the possible damaging effect of a ray consisting of radio waves. It was shown that the quantity of energy needed to upset an engine or hurt a person was far too great to be provided by any known method, but that the quantity of energy needed to detect the presence of aeroplanes or other objects might reasonably be produced by an extension of known means. The calculations incorporated in the paper had been done by Wilkins in half an hour. Watson Watt ended the simple statement with the comment that the difficult but much more promising problem of location by radio might be worth pursuing. These views were put to the Tizard Committee at its first meeting on January 28th, 1935.

The Committee asked Watson Watt to act on these ideas. The National Physical Laboratory provided him with the nucleus of a research team from within the staff of his own department. He rapidly produced a plan based on the radio echo method which he hoped would successfully find the distance, the bearing and the height of aircraft on a wide front up to a range of 100 miles ; and he suggested how friendly aircraft might be identified automatically. He also arranged a practical demonstration of radio waves reflected from aircraft in sufficient strength to be detectable at a distance.

On February 26th a van containing suitable radio receivers was halted at a place about ten miles from the powerful short-wave transmitters of the Daventry broadcasting station. A pilot was instructed, without being told the object of the flight, to take his aircraft over a course near the station. Strong indications of the reflection of the waves from Daventry by the aircraft were secured, and showed that the aircraft must be about eight miles away. (The interference beats in the carrier wave were very noticeable.)

It was subsequently appreciated that this experiment confirmed earlier observations of the reflection of radio waves by aircraft. For instance, the radio engineers of the British Post Office had noted in 1931 that interference effects appeared in their receivers whenever aircraft passed within four miles of one of their short-wave stations, and they deduced that these effects were due to reflection of the waves by the aircraft.

In March, 1935, the Tizard Committee recommended that large-scale experiments should be pursued. The Chairman, especially, pressed for action on an adequate and timely scale. The Treasury provided £10,000 for further researches. A new Air Defence Research Sub-Committee of the Committee of Imperial Defence was formed to include senior representatives of the three Services and of other departments, thus bringing various authorities concerned with radiolocation into collaboration.

A special laboratory was constructed at Orfordness, a quiet place on the Suffolk coast. In the meantime, Watson Watt and his small team worked on the design of the novel and powerful transmitter required, and on the receiving antennas, and amplifiers and cathode ray display systems for recording the echoes visually. They moved into the laboratory at Orfordness on May 13th. They became known as the " Islanders," owing to the isolation of the place. On June 16th the Tizard Committee visited Orfordness and saw an aircraft followed for more than 40 miles. On July 24th, while a " target " aircraft was being observed, a new trace appeared in the apparatus, revealing aircraft at twenty miles. A portion separated from this trace, and presently the remainder split into two. The whole was correctly diagnosed as a formation of three aircraft, one of which had subsequently broken from the formation at a distance of 15 miles.

By mid-September, the height of an aircraft, distant 15 miles and flying at 7,000 feet, was measured successfully. But an accurate method of determining azimuth or compass bearing had not been found. It was thought that two years' further research would be necessary to solve this problem. However, a solution came to

Watson Watt while in the train from Liverpool Street on the way to his usual week-end visit to Orfordness. In January, 1936, the bearings of aircraft, at 25 miles, were being measured with reasonable accuracy.

The research group now moved to larger premises at Bawdsey Manor, near Felixstowe. The full range (to the horizon) of a radar set is normally proportional to the square root of the height of the aerial-towers above sea level, and the original 70-foot towers were too low to stretch the increasingly sensitive detecting apparatus to its full range. At Bawdsey, new towers 240 feet high were built, and on March 13th, 1936, an aircraft flying at 1,500 feet at a distance of 75 miles was successfully located.

The actual horizon range for the 240-foot masts is only some 20 miles ; but the power radiated proved ample to detect aircraft, flying at a height (1,500 feet) sufficient to bring them within the space " illuminated," at the range of 75 miles.

The watchers at Bawdsey noted the movements of aircraft over the neighbouring areas of the North Sea. They knew more about the estimated time of arrival and place of landfall of the KLM airliners from Amsterdam, and the Deutsche Lufthansa airliners from Hamburg than the controller at Croydon airport. (They noticed a tendency of the DLH liners to make landfall near Bawdsey, and they wondered!)

The first Air Exercise in connection with radiolocation was held in September, 1936. The observers watched aircraft performing exercises over the North Sea, and were sometimes able to show the pilots that they did not know exactly where they had been, or that they had turned round the wrong lightship. They even detected aircraft slipping off to a nearby aerodrome for an early cup of tea, under the impression that their temporary absence from the sky would not be noticed.

Royal Air Force officers were trained to use the Bawdsey apparatus and by May, 1937, the Bawdsey station could be used in fighting operations. It became the prototype of a chain of stations erected to cover the Thames Estuary. A second station was opened in July at Dover and a third in August near Southend.

These stations gave the bearing and range of aircraft—the latter more accurately than the former—and the problem of correlating the tracks of aircraft from all the stations within range now arose. In action this would have to be reported quickly in intelligible form to the operations room at the headquarters of the Air Defence. An experimental " filter room " was started at Bawdsey, and became the first pattern of operational filter rooms.

The connection of stations with each other and with Air Defence headquarters required electrical communication lines which presently grew into an immense network. Their construction was carried out by the General Post Office.

Preparations for the construction of twenty watching stations, covering the coast and forty miles out to sea, and stretching from the Solent to the Firth of Tay, were begun in 1937. The choice of sites was a laborious task. The ideal site was one well back from the coast, with a smooth slope down to the sea. Hills sending back permanent radio echoes which would overlap and mask echoes from aircraft at the same range were to be avoided. The soil must be able to bear the weight of the steel towers, by now required to be 350 feet high, and the situation be convenient for station crews, electric power supplies, and transport for heavy machinery. The sites should be secure from naval bombardment, and inconspicuous from the air. The scientists had to survey the sites, and reason with irate landlords whose complaints included the objection that the erection of the gear, in some cases, might interfere with grouse shooting.

Soon after the trials of the chain of coastal stations started, its operators noticed aircraft whose tracks began and ended at Courtrai in Belgium. They enquired what airfield might be there, for none was on the maps supplied to them. Sometimes they were able to infer the direction of the wind over this distant field, from the direction in which the planes rose and landed.

The chain of five stations covering the Thames Estuary watched Mr. Chamberlain's plane flying to Munich in September, 1938, and a continuous twenty-four-hour watch for strange aircraft was started. By this time, £2,000,000 had been spent on the secret weapon.

On Good Friday, 1939, when Mussolini invaded Albania, a chain of twenty stations from Ventnor to the Tay started their continuous watch, which was never interrupted during the war except at one station which stopped for a short time owing to an unexploded bomb dropped by the enemy. Mussolini's forces also were being watched, for a station had been erected in Malta. Others were erected at Aden and elsewhere.

While the system of radiolocation was being developed at Bawdsey, methods of organizing fighter interception were being worked out at the R.A.F. Station at Biggin Hill, on the initiative of Tizard, who had pointed out that the introduction of radar rendered much of existing fighter tactics obsolete, and that new tactics to be used with radar required working out.

RADAR COVER
SEPTEMBER 1935

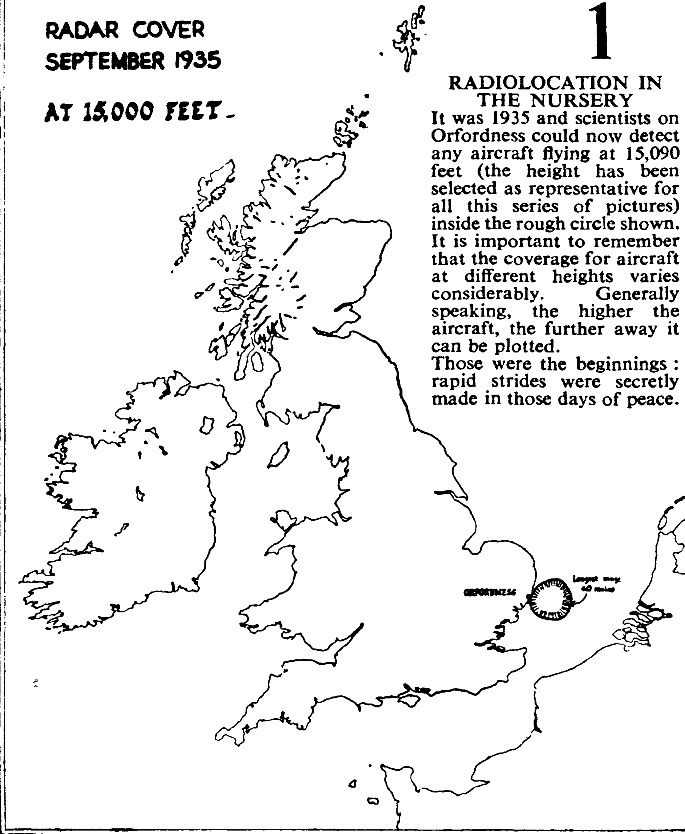
AT 15,000 FEET.

1

RADIOLOCATION IN THE NURSERY

It was 1935 and scientists on Orfordness could now detect any aircraft flying at 15,090 feet (the height has been selected as representative for all this series of pictures) inside the rough circle shown. It is important to remember that the coverage for aircraft at different heights varies considerably. Generally speaking, the higher the aircraft, the further away it can be plotted.

Those were the beginnings: rapid strides were secretly made in those days of peace.



RADAR COVER
SEPTEMBER 1939

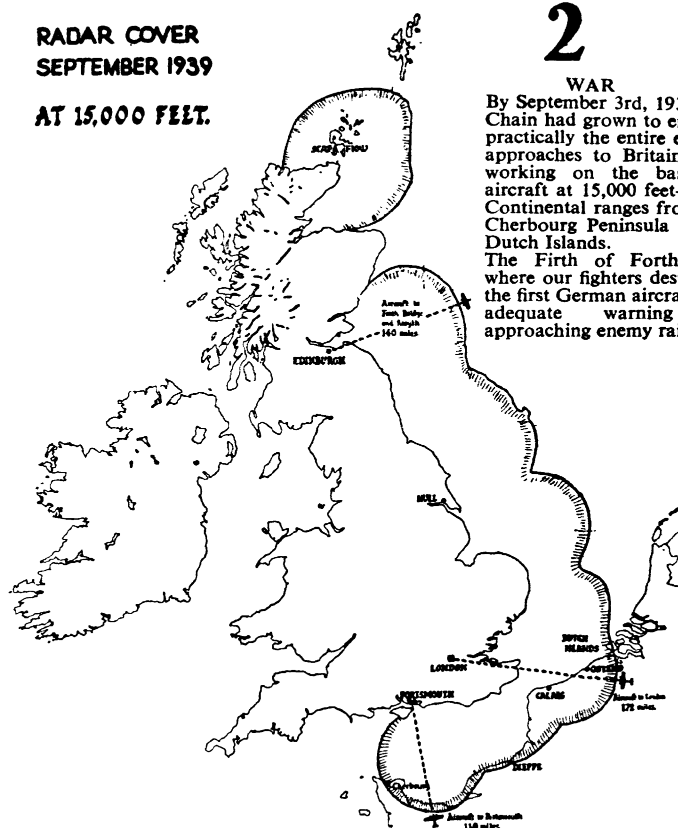
AT 15,000 FEET.

2

WAR

By September 3rd, 1939, the Chain had grown to envelop practically the entire eastern approaches to Britain—still working on the basis of aircraft at 15,000 feet—with Continental ranges from the Cherbourg Peninsula to the Dutch Islands.

The Firth of Forth area where our fighters destroyed the first German aircraft had adequate warning of approaching enemy raiders.



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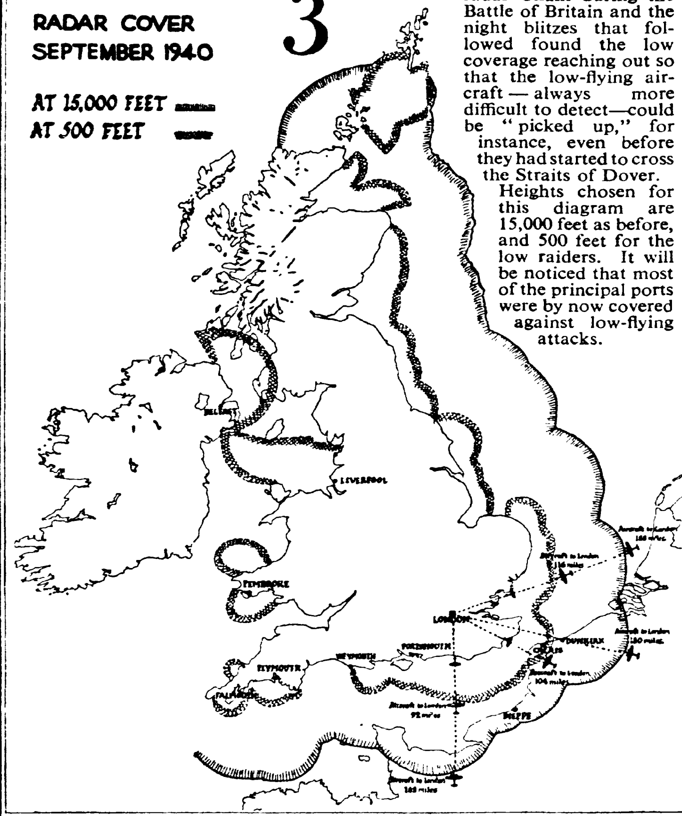
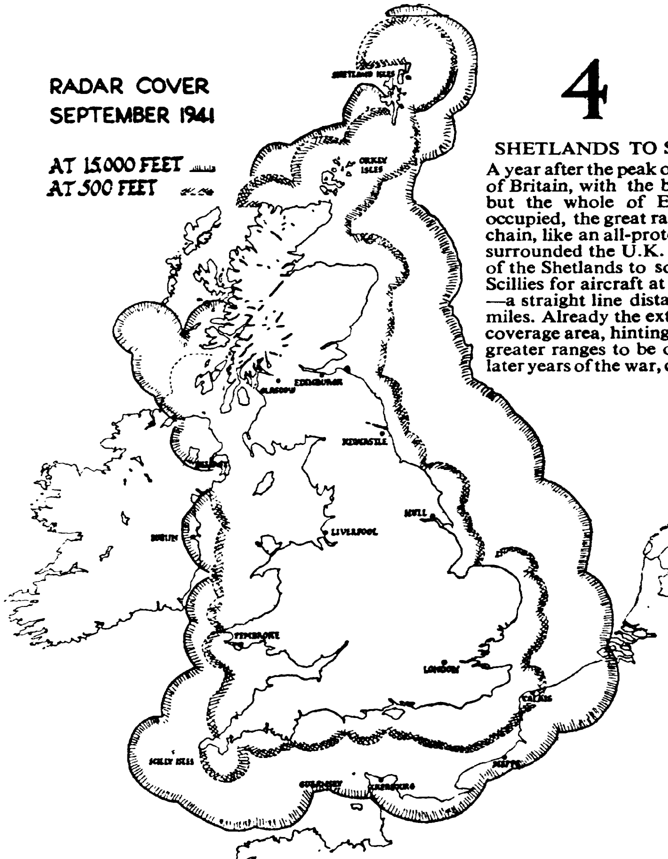


BATTLE OF BRITAIN

Testing time for the radar Chain during the Battle of Britain and the night blitzes that followed found the low coverage reaching out so that the low-flying aircraft — always more difficult to detect—could be "picked up," for instance, even before they had started to cross the Straits of Dover.

Heights chosen for this diagram are 15,000 feet as before, and 500 feet for the low raiders. It will be noticed that most of the principal ports were by now covered against low-flying attacks.

4



SHETLANDS TO SCILLIES

A year after the peak of the Battle of Britain, with the blitzes over, but the whole of Europe still occupied, the great radiolocation chain, like an all-protecting wall, surrounded the U.K. from north of the Shetlands to south of the Scillies for aircraft at 15,000 feet—a straight line distance of 900 miles. Already the extending low coverage area, hinting at the even greater ranges to be obtained in later years of the war, can be seen.

The scientific side of this investigation was conducted at Biggin Hill by Dr. B. G. Dickins. It was assumed that radar would in the future be able to detect aircraft at a distance of 50 miles to an accuracy of one mile, and a height of 1,000 feet. Long before radar capable of such a performance had been made, aircraft were fitted with equipment emitting radio signals, roughly simulating radar echoes, which could be picked up by direction-finding receivers. The tracks of approaching aircraft, flying in to the coast at a distance of fifty miles, were properly plotted and analysed. The first results showed the existing tactics for interception by day were very defective, and from this an adequate technique of controlling and directing was worked out.

Thus the development of the fighter tactics for use with radar was begun, and the fighter crews were trained in their use, before radar itself was developed. If the R.A.F. had waited to work out fighter tactics until radar had been developed to a considerable degree there would not have been time to elaborate the new tactics and train the crews. Without this far-sighted development of tactics at Biggin Hill, the R.A.F. could not have efficiently utilized the advantage given to them by radar in the Battle of Britain.

On the basis of observations provided by Bawdsey, nearly all airliners approaching England after January, 1938, were subject to concealed mock attacks by fighters directed from Biggin Hill. The data received there at the Operations Room were originally handled with the aid of complicated calculating aids. One day the R.A.F. officer in control observed the data and concluded that he could deal with most of it mentally, without using all of the instruments. The system of Day Fighter Control used in the Battle of Britain was evolved from the method that he introduced.

Thus, in September, 1939, the east coast of Britain was surrounded by invisible radio waves. Aircraft approaching at a height of 15,000 feet were detected by them more than 100 miles away, through night, cloud and rain. Their number could be counted and their evolutions watched.

In order to produce this result, the scientists had to concentrate on a wide diffusion of rays—radar " floodlighting " : fascinating possibilities, which were developed years later, had to be sacrificed to the one objective of a continuous unbroken watch. Their first job was " to make England an island again " ; and they succeeded, with scientific genius and the expenditure of £10,000,000 secretly.

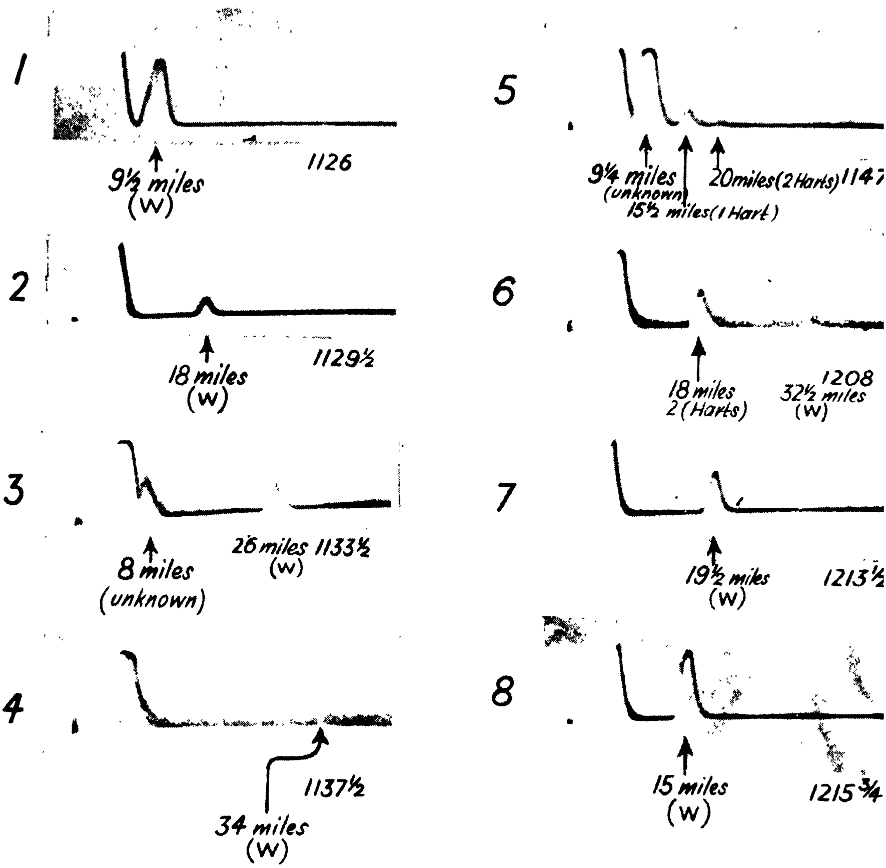


PLATE I

On 24th July, 1935, an experimental flight of a Wallace aircraft was made under continuous radar (R.D.F.) observation. Photographs of the oscillograph screen were taken between the beginning and end of the flight which lasted from 11.26 until 12.15. These eight pictures are reproductions of the original photographs. The echo from the Wallace is marked (W) to distinguish it from other echoes.

The outgoing pulse is shown (only partially) on the extreme left of each picture and the returning echoes are the " blips " to the right. Those further to the right are from the greater distance (stated on each picture) and in general the more distant echoes are the fainter.

Pictures 5 and 6 show the intrusion, unexpected but interesting, of three Hawker Hart aircraft whose echoes are marked.

They were inferred to be a flight of three, one of which subsequently broke formation and flew off.

This was the very first radar observation of a flight of several aircraft—the interpretation was subsequently confirmed by the Wallace pilot who had himself observed the Hart aircraft flight.

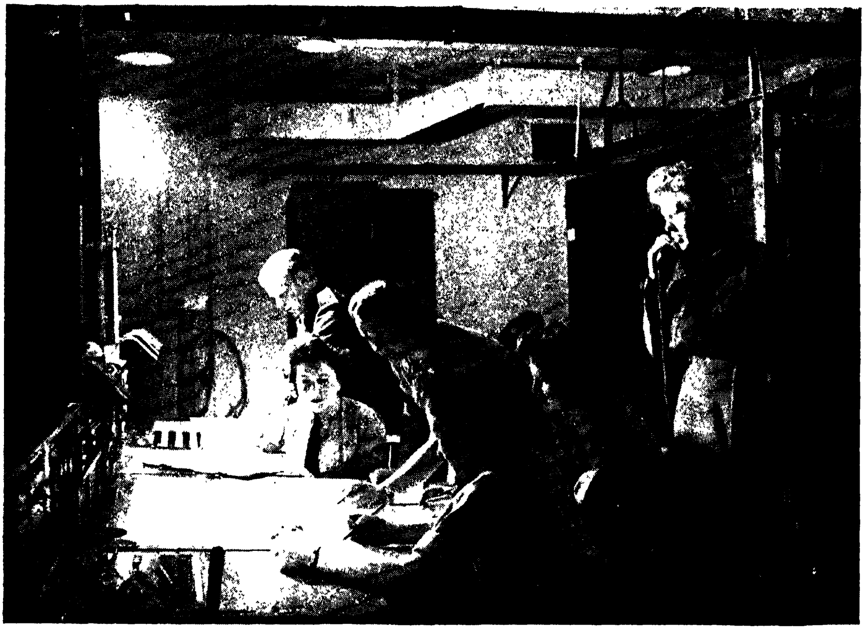


PLATE II

Women of the W.R.N.S., A.T.S. and W.A.A.F. worked under great secrecy and with the utmost efficiency during the war, on radar apparatus. They not only helped in assembling the gear, in training personnel and often in servicing apparatus, but tracked hostile and friendly aircraft, flying bombs, German E boats and Allied merchant ships. They carried out their duties with immense enthusiasm often under onerous conditions of discomfort and enemy fire.

These two pictures show W.A.A.F. at work with a R.A.F. sergeant in a radar station operations room under the shadow of a 360-foot lattice mast shown towering up on the right.

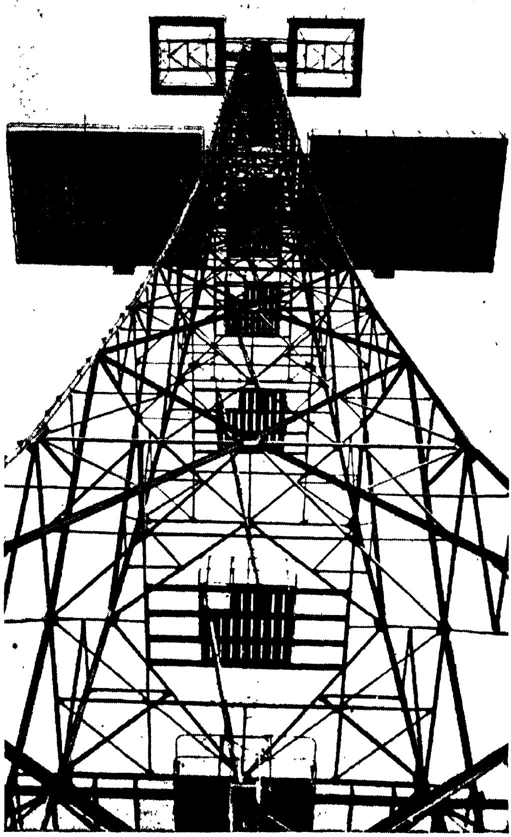
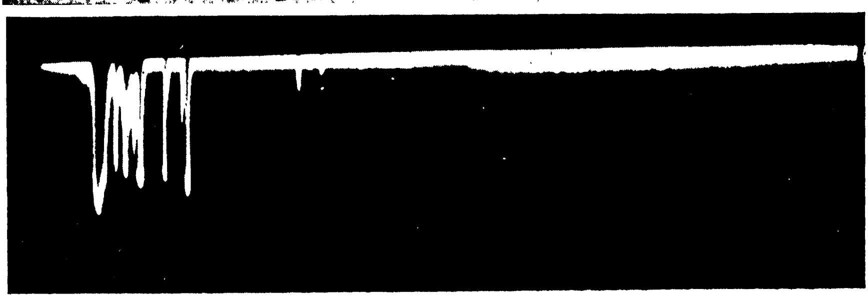
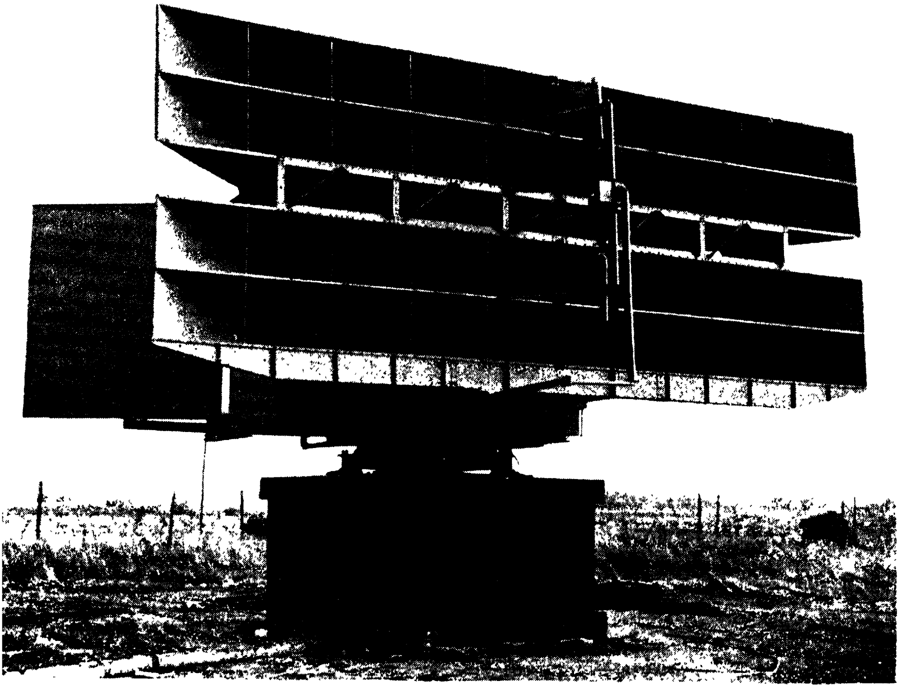


PLATE III

A C.H.L. (Chain Home Low station is shown on the left. Th important features are a powe rotated aerial stack on a mas 185 feet high and a simila lower one on a 20-foot gantry The kind of trace seen by th operator is shown below The short arrow on the left i: the main pulse sent out, thos near it are fairly close objects but the " blips " to note ar pointed by the two talle arrows and are echoes fron aircraft 50 and 55 miles away





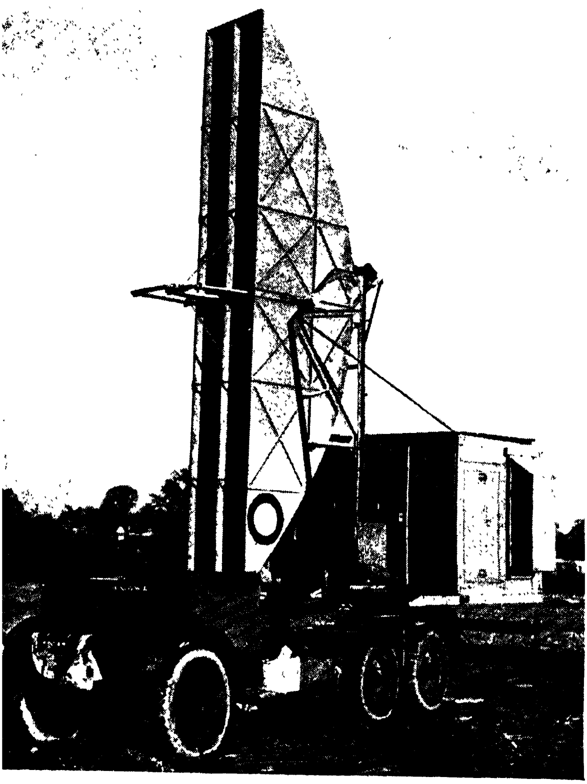


PLATE IV

When power could be produced from magnetrons on a wave-length of ten centimetres, " cheese " aerials were adopted for radar height-finding equipment. This choice of name is clear from the pictures which show two forms of this aerial. The vertical one gives flat beams shaped like a lady's fan held horizontally and waving up and down. The horizontal one gives a flat beam like such a fan held vertically and waving sideways.

Watching

THE THREE NECESSARY MEASUREMENTS

THE watcher at a radiolocation station who is looking for approaching aircraft needs to know three things about any aircraft that comes under his observation. He needs to know the distance between himself and the aircraft—this is called the " range " ; he must also know how much to the east or west of his north-south line the machine is—that is, the " bearing " ; finally, to fix unambiguously the position of the machine in the sky, he must know at what angle upwards from the horizontal he must look to see it—this upward sighting angle is called the " elevation."

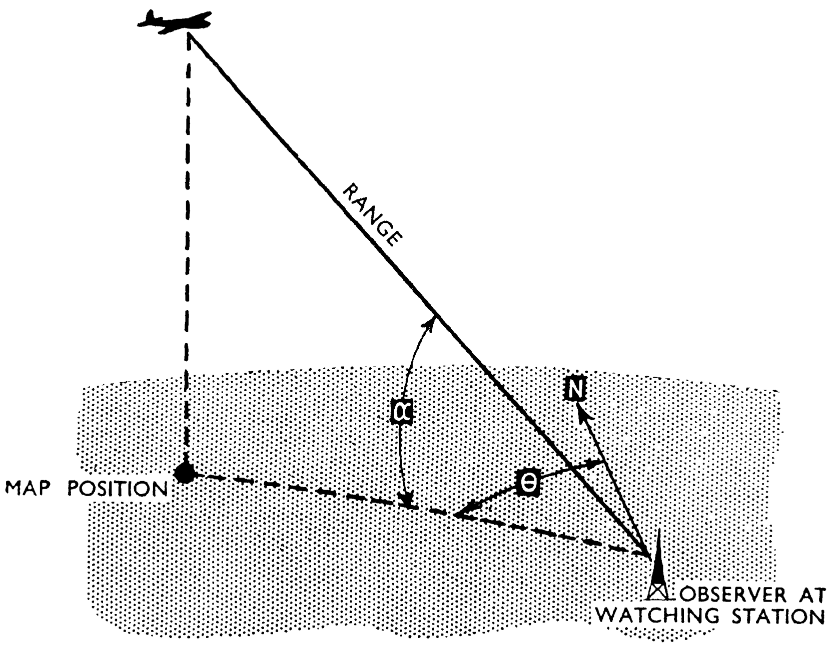


FIG 2.— θ is angle of bearing and α is angle of elevation of aircraft.

In Fig. 2 we have represented a rectangular portion of the earth's surface, with a radiolocation station and observer. To the west of north, an aircraft is approaching. The three quantities needed to determine its position are the range, the angle of bearing θ,

and the angle of elevation α. The angle of bearing can be found by a combination of receiving aerials at right angles to each other, from which the direction in the horizontal plane can be determined. The angle of elevation is found from two aerials, one placed higher than the other. The explanation of how this works will be given later.

The Distance : as the Echo Flies

The direct distance of the aircraft (the range) is found from the measurement of the time taken for a radio wave to travel from the transmitter to the aircraft and back after reflection. This measurement of the range purely through action at the observer's base, and not depending on any action on the part of the crew of the aircraft, such as sending out radio waves to their own home base, is the most novel and important feature of radiolocation. First, it enables the aircraft to be located without the crew's knowledge, or in spite of anything that the crew can do. Secondly, all three measurements—the angles of bearing and of elevation and the range—can be measured from the observer's single station. It is not necessary to have two stations in order to measure the range of the aircraft. In ordinary radio direction finding systems, where the range cannot be measured from one point, but must be measured from two points at the ends of a base of known length, as in Fig. 3, it is evident that the calculation of the range of the aircraft from the four angles and the base length is much more complicated than as in Fig. 2.

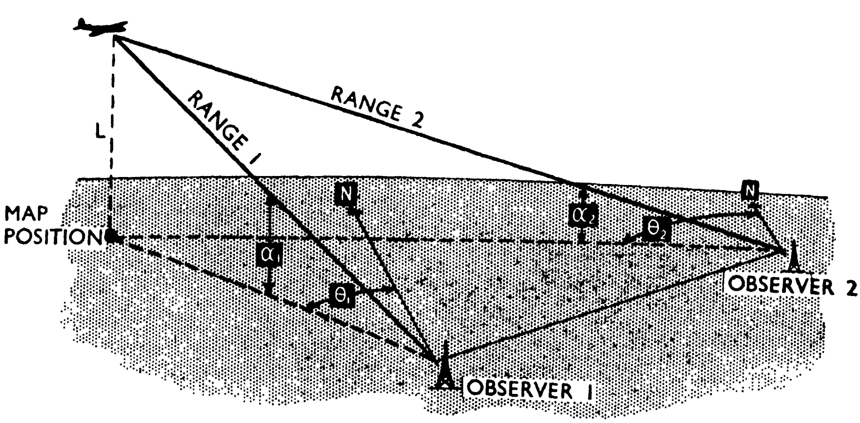


FIG. 3.—In this diagram is shown how, on the old direction-finding plan, Radio co-operation by the aircraft is required for the position of the aircraft to be found. Observers at 1 and 2 with special receiving apparatus must measure two angles of bearing θ_1 and θ_2 as well as two angles of elevation α_1 and α_2 before the position of the aircraft in space can be calculated.

The possibility offered by radar of the observer measuring the range from his own single station, without simultaneous observations from a second point, gives him a new degree of freedom.

The location of an aircraft by the older method depends, as we here see, on the measurement of two angles and a length. But by radar, instead of having to use a clumsy method of comparing the range with a long fixed length marked on the surface of the earth, the observer gets his length directly : he emancipates himself from dependence on any second observer and on the need for reference to a long fixed base line comparable in length with the range to be measured. The observer is given one unit of equipment, in which transmitting aerials, receiving aerials, and direction-finding aerials for determining bearing and elevation, are compactly combined. But before this unit will work, many technical problems have to be solved.

The Pulse

Is the range to be measured by the method first used in measuring the distance of the Heaviside layer ? In this case the radiolocation station in Fig. 2 would have to send out a wobbled wave, whose frequency is being rhythmically varied. The reflected wave, when it returns, will have a frequency slightly different from that of the new wave just setting out from the transmitter. Hence, beats will occur. From the frequency of these beats, the time taken by the wave to travel from transmitter to aircraft and back can be calculated. The time is equal to the frequency of the beat divided by the rate of the modulation, or rate of change of the frequency of the transmitter wave. From the time taken, the range immediately follows for the wave travels at 186,000 miles a second.

This system would not, however, be practicable for locating several different reflecting aircraft simultaneously, because there would be a confusing medley of beats difficult to interpret. It is therefore desirable that each echo should arrive in a sharply defined form, and distinct from every other echo. This is achieved by using the system of radio pulses introduced by Breit and Tuve in 1925, and developed later in Britain by Appleton and his research school.

In this system, a short train or "jab" of radio waves lasting a very small fraction of a second is emitted ; this goes off, is reflected by the aircraft, and returns. If the pulse is made to mark the moments of departure and return on a time-scale, the time of its journey, and hence the distance of the aircraft, is given automatically. Single aircraft in flight are normally separated by considerable

distances, and will in general be at different distances from the observing station, so their various echoes will arrive at the receiver at different times and will be recorded by marks at different places on the time-scale. The pulse must be short enough to produce echoes clearly separated in the receiver even when the aircraft is near to another aircraft or to the observing station itself. To distinguish between two aeroplanes one-tenth of a mile apart along the direction of the receiver, the pulses must be not more than a millionth of a second in duration, as the waves travel at 186,000 miles a second. A pulse setting out, and one returning to the observing station are depicted in Fig. 4. This corresponds to the shout or bang which a mountaineer may make in order to produce an echo by which he can estimate the width of a valley, or his distance from a cliff. The shorter and sharper the sound, the more

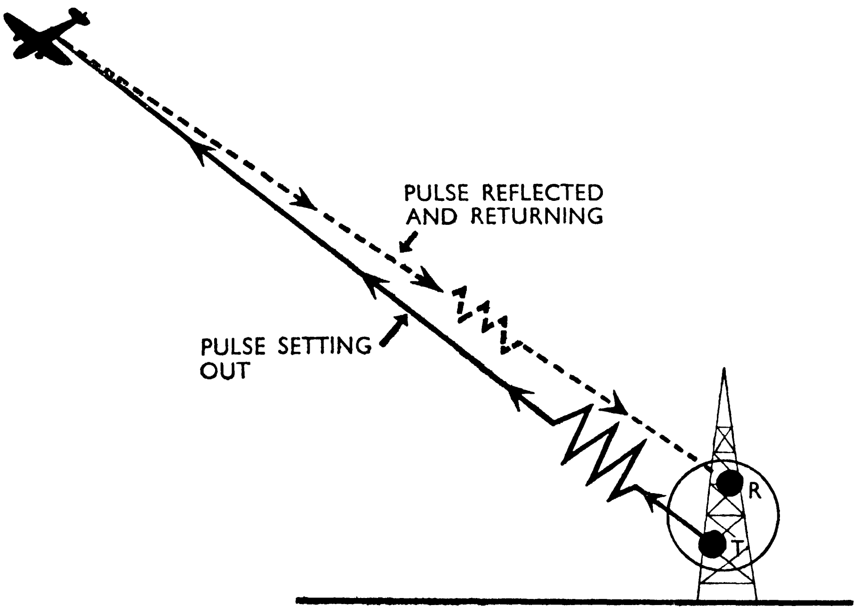


FIG. 4.—This diagram shows the simplest pulse radar scheme, in which a strong pulse of waves lasting only a few millionths of a second is sent out from the transmitter T, and is reflected back, much weakened, to the receiver R. The time interval between the outgoing pulse and returning echo tells the observer the range of the aircraft.

accurate is his measurement of the interval between the making of the noise and the return of the echo, and hence of the distance.

A transmitter sending out a series of pulses of a duration of

two to ten millionths of a second is required, and a method of recording and sharply distinguishing such very transient events. The artificial pulses from the transmitter resemble in some ways the natural pulses sent out by a lightning flash and which constitute an atmospheric. It is not surprising therefore that methods which proved successful for investigating atmospherics should be adapted to the recording of the departure of radio pulses, and the arrival of their echoes.

One of the first subjects of research by the Radio Research Board in Britain was atmospherics, which so disturbed the early broadcasting receivers. It was necessary to discover their nature and origin, in order to mitigate their effects. The first effort to locate them was made at Farnborough in 1915, to enable flying men to avoid storms. The Radio Research Board founded a special laboratory for these researches in 1920 under the superintendence of Watson Watt. The atmospheric is a very brief phenomenon, and therefore needs some very quick method of recording. Watson Watt and Appleton independently suggested that a cathode ray tube would be suitable for finding the wave-form of the atmospheric. Subsequently, Watson Watt adapted it to carry out a proposal, which he had made in 1916, for locating atmospherics in the following way. If (as in Fig. 5) two loop aerials A and B are set up at

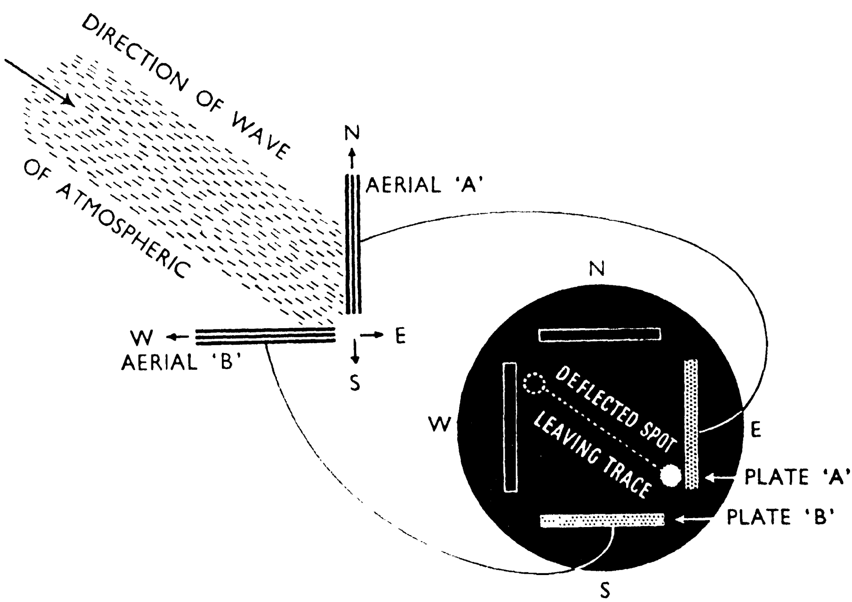


FIG. 5

right angles, and connected to two pairs of parallel plates aa and bb, inside the tube, at right angles to each other and parallel to a beam of electrons in the tube, then the waves from a distant atmospheric falling on the aerials will raise the voltages of the two plates according to the proportion of the energy falling on the respective aerials, which in turn depends on the angle of incidence of the direction of the atmospheric with the aerials.

The spot made by the undisturbed cathode ray, will move under the electric forces produced by the plates A and B. The direction of motion will be the same as the direction of the atmospheric, since the plates A, B are connected to aerials A, B. Atmospherics usually last about 1/1,000th of a second. The trace of the spot in its rapid movement will be revealed by the after glow of the phosphorescent material with which the face of the tube is coated. Thus the direction of atmospherics was directly and visually recorded. The location of their origin follows from the use of the two such tubes connected to pairs of aerials at the ends of a base line. It was proved that all atmospherics originated in electrical storms and thunderstorms.

A cathode ray tube for radiolocation is shown diagrammatically in Fig. 6. A stream of electrons is projected from the cathode, making a steady spot on the fluorescent end of the tube. An electric circuit starts a voltage between the X-plates and makes the spot sweep at a constant and known speed from A to B. The same mechanism which starts this voltage also makes the transmitter send out a pulse. This reaches the receiving aerial immediately, and produces a voltage which is transmitted to the Y-plates. The voltage on the Y-plates is raised for a few millionths of a second. Hence, just after the spot begins to sweep towards B, it gets a sudden jolt downwards making a "blip" or "break" which marks the moment of emission of the pulse. Meanwhile the pulse flies on, reaches the aircraft, and is reflected back as an echo. When the echo arrives, it produces a fresh voltage on the Y-plates, producing the echo blip. As the spot moves from A to B at constant and known speed, the distance between the respective blips due to the pulse and the echo is a measure of the time taken by the pulse to reach the aircraft and return, and hence is a measure of the distance, or range, of the aircraft. Moreover, the distance on the tube is immediately visible to the eye, and can be read off at once if a transparent scale is attached to the tube from A to B.

The Y-plates are never entirely free from stray voltages. Some of these come in from the aerial, and others from the valves and circuits, electrical connections and disturbances in the instrument.

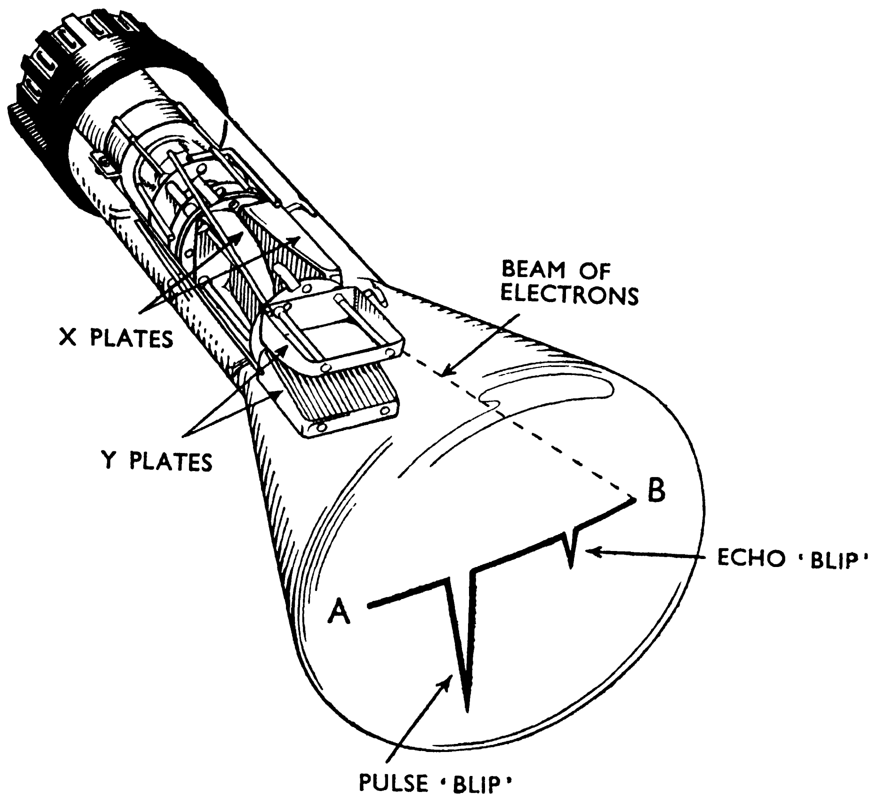


FIG. 6.—The " X " plates influence the beam so that it traverses the screen from A to B while the pulse in Fig. 4 is travelling to the aircraft and back as an echo. The outgoing pulse and returning echo make the " blips " shown. Pulses are sent out at rapid, regularly recurring intervals, so that the position of the echo on the screen at any moment of time gives the position of the aircraft. A scale on the screen can give the range in yards or miles as required. No calculations are necessary in that case.

These stray voltages roughen the track of the spot, and cover it with ever-changing small indentations. They are a form of natural "jamming." An echo must therefore be strong enough to make a blip big enough to be distinguishable from, that is, to emerge through, these rough ever-changing indentations.

The pulse is reflected by surrounding hills, buildings, and obstructions of various kinds. These produce a series of permanent echoes, which tend to mask the genuine echoes—though they have some value as reference points.

In the British identification system friendly aircraft carry a small

set which picks up the radiolocation signal, amplifies it, and re-radiates it with the echoes. When these are registered on the receiving tube, they carry the signal's specific mark. Thus our own aircraft are automatically identified and distinguished from those of the foe. The friendly fighter pilot is relieved from the fear that he may be pursuing a friend, and the friendly bomber pilot that he may be mistaken for a foe. The system also enables the anti-aircraft gunner to avoid firing at our own aircraft, and enables the bomber returning home to be identified automatically. Wilkins and Dr. F. C. Williams originally developed this identification system from Watson Watt's basic proposals.

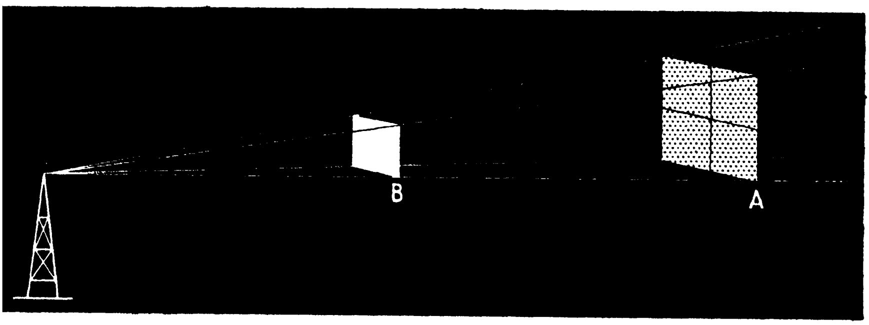


FIG. 7

The radiolocator requires as strong an echo as possible in order to detect aircraft at a maximum distance. Now it can be shown by a simple calculation that if you wish to double the range of your radiolocator to a target in free space, you must multiply the power that you put into it by at least sixteen times. Thus, in so far as the range of a radiolocator depends on the electrical power put into it, big increases in power are necessary to secure even a small increase in range. This is illustrated in Fig. 7 where a square cone of rays is shown diverging out from the radio tower and passing through two square areas B and A at right angles to the rays. A is twice as far from the tower as B. The same amount of " light " passing through B is spread over the larger area A, which by geometry can be shown to be four times as large. An aircraft flying at A is therefore less brightly " illuminated " than an aircraft at B by a factor of four ; the reflected echo when it starts from A will thus be $\frac{1}{4}$ the strength of that from the position B. The echo will also spread out in space and weaken in exactly the same way to $\frac{1}{4}$ by the time it gets back to the tower, the result being $\frac{1}{4} \times \frac{1}{4}$, or $\frac{1}{16}$. Thus

to get a " blip " of the same size from an aircraft at A needs 16 times the radiated power which would be necessary with an aircraft at B.

It has been in the past, in general, easier to secure high power with long waves, for they can be generated with the more orthodox large radio valves, not only because these are easier to make but also because manufacturers have had long and intimate experience with them and know their ways well. When specially made for short wave-lengths, valves of this type must be made small in size and with close clearances between the electrodes : they get very hot when any power is put into them, a fact which most seriously limits their application in practice.

Advantages of Short Waves

Other needs are, however, in favour of short waves. The Heaviside and other ionospheric layers do not usually reflect radio waves appreciably shorter than about 10 metres. The use of waves of less than 10 metres' length is preferred in radiolocation sets operating on the echo principle, because this eliminates echoes from the ionosphere which might confuse the record of the echoes from aircraft, which reflect these short waves quite well.

A second reason why short waves are desirable is that they are more easily directed. The effective power of a radiolocator can be greatly increased by focussing the waves in the direction of the sought aircraft. If the waves are long, an enormous focussing mirror, or an enormous aerial " array," would be needed, which would be impracticable. Hence short waves, which can be focussed with mirrors or other arrangements of practicable size, are desirable.

Another advantage, to be explained presently and of great importance, is that the disturbance to detecting beams by interference from reflections of themselves from the earth's surface is less serious with short than with long waves. As a consequence, low-flying aircraft are detected better by shorter than by longer waves.

Aerials and their Plumes of Waves

Our senses are directly affected by light and by sound. A source of light is as necessary as a source of sound, and such sources are merely means of sending out the necessary waves of light or waves of sound in the media in which these waves travel. A gong struck in the middle vibrates to and fro with a definite frequency, the middle part bulging in and out and sending out waves of compression and rarefaction invisible to the eye but audible to the ear. These waves involve a to-and-fro motion of the air in the

same direction as the propagation of the sound : they depend for their existence on the nature of the air through which they pass and in particular on its elastic properties. Light waves, although they pass through air, pass equally well through a space not containing air. Light consists in fact of waves electrical in nature, differing essentially from sound waves in that their vibrations are executed *at right angles to*, and not along, the direction of propagation. Radio waves are of exactly the same nature as light waves ; they are electrically propagated in straight lines: the waves executing their vibrations at right angles to the direction of travel. Just as a vibrating gong is the source of sound, so the electrical vibrations in an aerial are the source of radio energy.

Among the simplest kinds of aerial are metal rods half the length of the wave in use ; and in view of what we have just said it will be seen that such an aerial, when in electrical vibration with the electrons oscillating to and fro along its length, will send out energy in all directions except the direction in which the electrons are moving ; thus no radio waves travel out along the line of the aerial. A kind of chart can be drawn showing quantitatively how such an aerial radiates into space. We can just draw a line in the direction we are considering and make its length proportional to the amount of radiation travelling in that direction. It is a little complicated to see how this transmission occurs in all directions in space, but an infinite series of such lines will form a solid figure of symmetrical shape if we imagine the half-wave rod or dipole at its centre of figure. The shape of its three dimensional curve is rather like an apple with a very deep dimple at each end meeting in the middle, where we can imagine one pip—the dipole.

If the apple is cut in half vertically through the dimple, the cut edges will give the appearance of the curves shown in Fig. 8B, and this is the kind of way in which one generally thinks of the radiation from an aerial spreading out in plumes in space. If such an aerial were used in practice the radiation could not be relied upon always to detect an oncoming aircraft because the enemy could always steal in, as it were down the dimple in the radiation.

The very simple aerial we have been thinking of is directive to a moderate degree—it transmits and receives badly in the direction of the dimple, moderately well in directions at right angles to that axis. Designers of aerials, however, have been at pains to put aerials together in carefully thought out " stacks " or " arrays " so arranged as to introduce directive properties in a high degree—so useful for concentrating the available energy in certain directions and for receiving echo energy selectively as well. Such aerial arrays

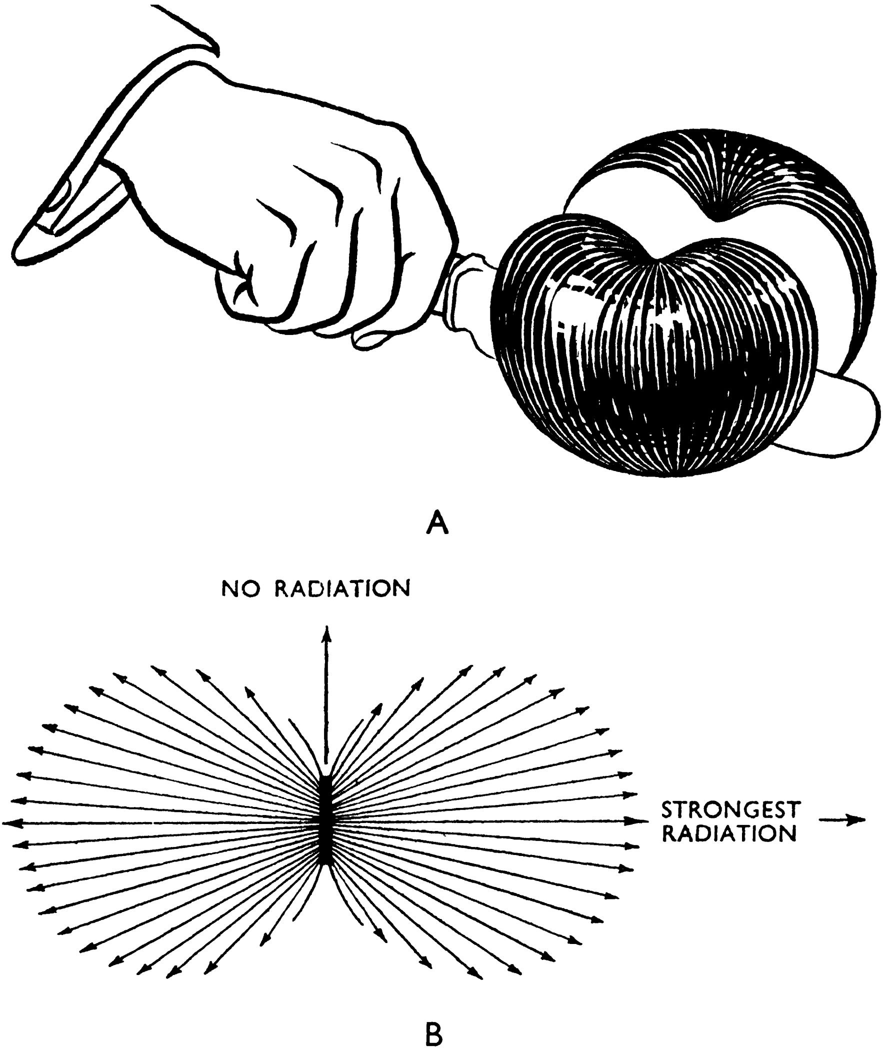


FIG. 8.—A way of diagrammatically representing the radiation strength in the space around an aerial is to imagine straight lines radiating out in all directions, the length of each line representing the strength in its particular direction. The ends of these lines lie on a solid surface. Equal radiation in all directions would give a sphere but the simplest aerial, a short straight " dipole " well away from the ground gives a surface with two deep dimples like an apple (Fig. 8A). Cut in half the section (Fig. 8B) gives the general shape of the two plumes or lobes. The little dipole is seen in the middle.

by combining good transmission and good reception are able to make fuller use of the available energy—in technical language may have a high " gain," and for this reason are preferable to the simple

dipole. They may suffer all the same from the disadvantage of dimples down which the enemy may be able to steal.

How are differently shaped plumes of waves produced? In the case of the earlier radar sets use was made of the surface of the earth, which generally acts as a reflector of radio waves and thus influences the direction and number of the plumes of waves, or lobes, emitted from a transmitter mounted near its surface. This is due to the mutual interference of waves which are reflected from the surface of the earth with those proceeding direct from the station. Wherever crests of these waves meet in space they will reinforce each other, wherever crests and troughs meet there will the wave be non-existent. It is as if there were two aerials emitting simultaneously, the actual one and its mirror image in the ground. The result of this reflection from the earth's surface is to modify profoundly the curve showing the distribution of waves. It is no longer so simple as when the dipole was imagined to be quite isolated in space and the kind of curve is shown in Fig. 9. It is this interference of waves which causes the curve to be split into adjacent plumes. Along the lines ON, ON_1, ON_2, and so on, there is no strength at all as the direct and reflected waves cancel each other out.

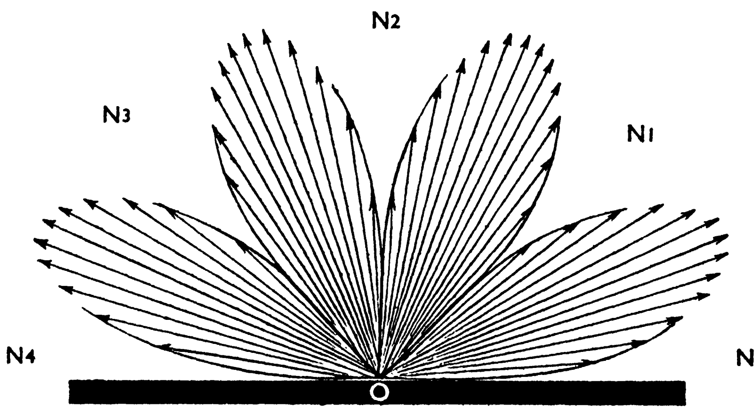


FIG. 9.—When a dipole is near the earth, as at O, the plumes are more complex than in Fig. 8 because of the mutual interference of waves coming direct and by ground reflection. The ground surface shown here is horizontal and no radiation in this case reaches this low level (N). There is no strength either at N_1, N_2, N_3, N_4.

The number of plumes depends on the ratio of the height of the aerial to the length of the radiated waves. Thus with short waves and high aerials the number of plumes increases. Suppose the wave is shortened, so that the number of plumes increases to eight,

as in Fig. 10, then it is clear that the angle of maximum wave-strength in the lowest plume will only be about half that of the corresponding angle in Fig. 9.

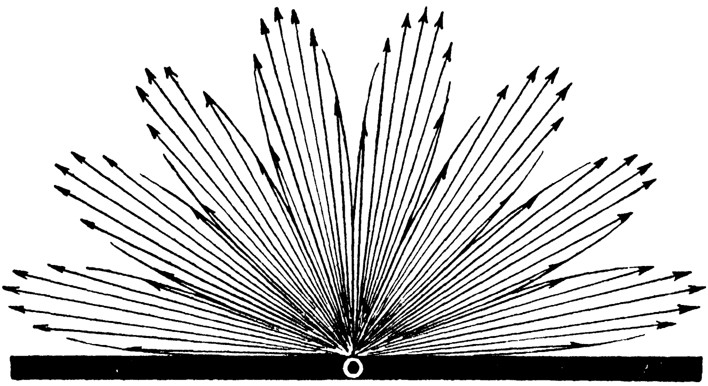


FIG. 10.—This diagram is similar to the previous one—the only difference being that the wavelength has been shortened. A higher aerial produces the same effect. Notice that the lowest plume is here much closer to the ground than in Fig. 9. A very low flying aircraft, however, could still steal in.

Thus the higher aerial and the shorter wave will give much better detection of low-flying aircraft. This is why the early watching stations, which did not use the shortest waves, had aerials on towers 350 feet high.

Compact Aerials

Going back once more to the very convenient aerial known as the half-wave aerial or dipole, a particularly useful and quite simple form of aerial makes use of a stack of these rods ranged in the manner shown in Fig. 11A. This arrangement was invented by the Japanese, Yagi. In the war of 1941-5, Yagi was the director of the Japanese scientific effort. He was trying to develop concentrated beams of short radio waves of 80 centimetre wave-length which would kill animals at a distance. He has stated that he succeeded in killing a rabbit at 30 yards, but that muskrats were much more resistant. These absurd attempts to develop a " death-ray " of military value, in the nature of the case, of course, failed. But we used his invention more profitably. Yagi's array gives a fairly concentrated plume of waves by making use of the principle of interference of the waves sent out from this set of dipoles and reflected from the reflector. The direction in which the plumes are pointed, or the " shoot," as it is called, is the direction shown

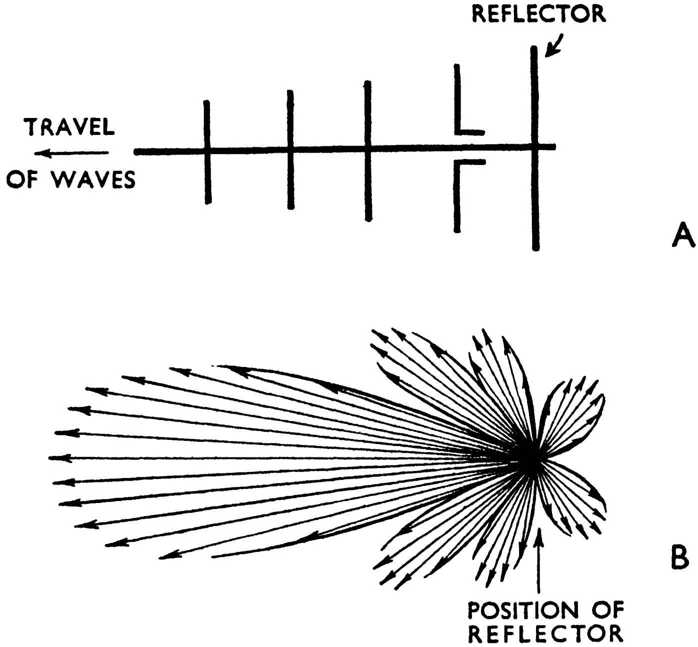


FIG. 11.—This type of aerial is known as the Yagi aerial. The stack includes a reflector rod and it will be seen from (B) how the radiation is flung forward. The central plume is very strong indeed.

in Fig. 11B. It will be seen that the energy is nearly all flung in the forward direction and is contained within an angle of 20° to 40°.

Aircraft used aerials of this type quite a lot, and they are particularly noted as being small, compact and can be made fairly streamlined. These aerials operated well at about a wavelength of 1½ metres. But the sharpest beams are obtained with very short wavelengths made practicable with the advent of valves capable of producing a wavelength less than 10 centimetres. Aerials only an inch long or less became possible and could therefore be mounted in mirrors, or built up into very small stacks indeed. By the use of these mirrors very sharp plumes of radiation, of only a few degrees divergence and with quite negligible side plumes, became possible.

These beams are produced, in a way not unlike the familiar searchlight beams, by mounting the radiating dipole at the focus of a concave mirror (usually paraboloidal). A beam is sent out with an angular spread determined by the wavelength used and the size of the mirror. A large mirror gives a slightly spreading beam, a smaller mirror a more spreading beam. To get an effective beam,

however, the mirror must have a diameter 10 or so times as large as the wavelength of radiation used.

The Angles : Electrically Measured

As has been explained, the *bearing* of the aircraft may be found by comparing the strength of the echoes from two aerials at right angles to each other. Another method consists in directing the plume first to one side of the aircraft and then to the other, by means of a periodic change in the electrical currents which feed the transmitter aerials. The diagram of the plumes shown in Fig. 12, indicates how the strength of the waves in the direction of the aircraft is greater when they are radiated in the direction P_1 than in the direction P_2 (in the proportion of OX_1 to OX_2). Hence the strengths of the echoes in the respective cases will be in this ratio. If the apparatus is mounted on a turntable at O, it can be rotated until the echoes from both plumes are equal. The direction of the aircraft will then be on the line bisecting the angle between the two plumes (the dotted line, in Fig. 12). This " split-beam " method of direction-finding gives very accurate results. It was developed by Mr. W. A. S. Butement and introduced in the first accurate coastal defence unit designed in 1939.

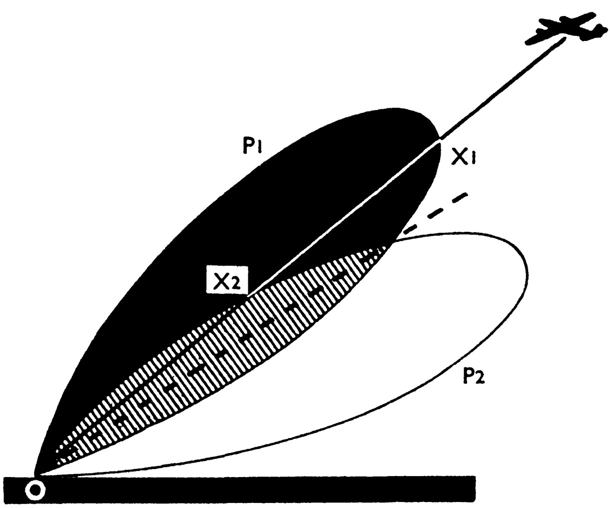


FIG. 12.—Illustrating the " split beam " method of accurately determining the direction of an aircraft. The plumes P_1 and P_2 do not exist simultaneously but are alternative positions produced by switching. This is done rapidly and continuously and the echoes observed. When the aircraft is symmetrically held, that is when it is on the dotted line, successive echoes are of equal strength.

The *angle of elevation* of an aircraft was originally measured with the aid of two aerials, one placed higher than the other : difference in height, as has been explained, alters the number and direction of the plumes. In Fig. 13, the lower aerial produces the high broad

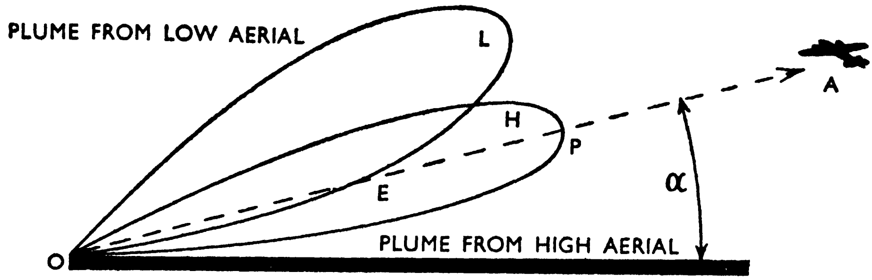


FIG. 13.—Showing how a combination of high and low aerials can indicate the height of an aircraft.

plume L, while the higher aerial produces the lower narrower plume H. The strengths of the radiated waves, from the higher and from the lower aerials, in the direction of the aircraft, are in the proportion of OP to OE, and the respective echoes will be in the same proportion. Corresponding to every angle of elevation there will be a definite proportion. Hence, if a table of this relation is made, the angle of elevation of any particular aircraft can be read off at once from the proportional strengths of the echoes recorded by the two aerials.

One defect of this system is that its accuracy depends on the character of the earth's surface near the station. This is always more or less uneven, so that reflections are not symmetrical, and the plumes are distorted. An obvious improvement is to replace the earth by an accurate metal reflector or directive system. This is possible, except for certain special cases, only with short waves, as the reflector for 10 metre waves would be impracticably large. When shorter waves were introduced, it became possible, as we have seen, to direct a sharper radio beam (a " radio searchlight ") towards the aircraft, and determine the latter's direction by swinging the beam round until the position of maximum echo, and hence the exact elevation, was found.

The beam from such a " radio-searchlight " differs, however, from that of an optical searchlight. As the wavelength is comparable with the width of the mirror, the beam is like that of a ray of light passing through a very small hole—the beam is split into diffraction rings, with a bright ray in the middle.

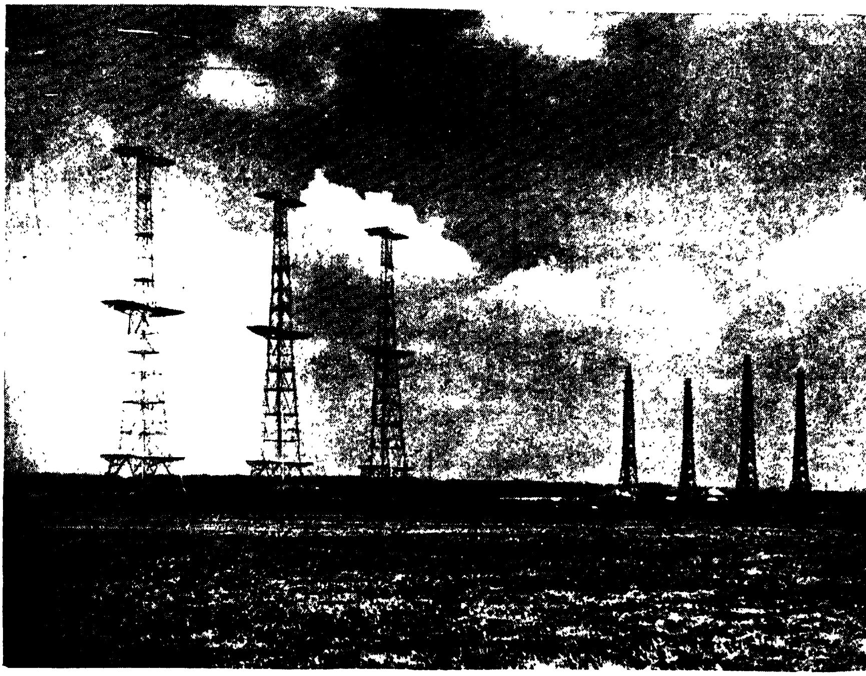
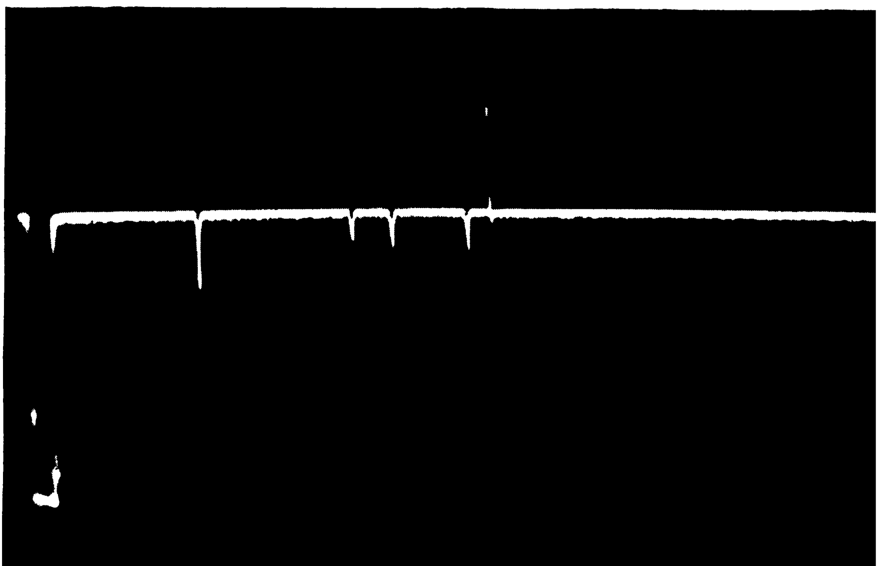


PLATE V

A typical high mast C.H. (Chain Home) station is shown above ; the kind of trace seen on the oscillograph trace is shown below. As usual, the distance of the " blip" from the transmitter pulse gives the distance of the aircraft. Since the C.H. station " floodlights " the sky, the precise direction of the enemy is not known. A knowledge of his actual range, however, was of paramount importance. Four separate aircraft are here shown with their down-pointing " blips." The narrow up-pointing one is a marker, which can be moved along by turning a pointer moving over a scale which gives the mileage.



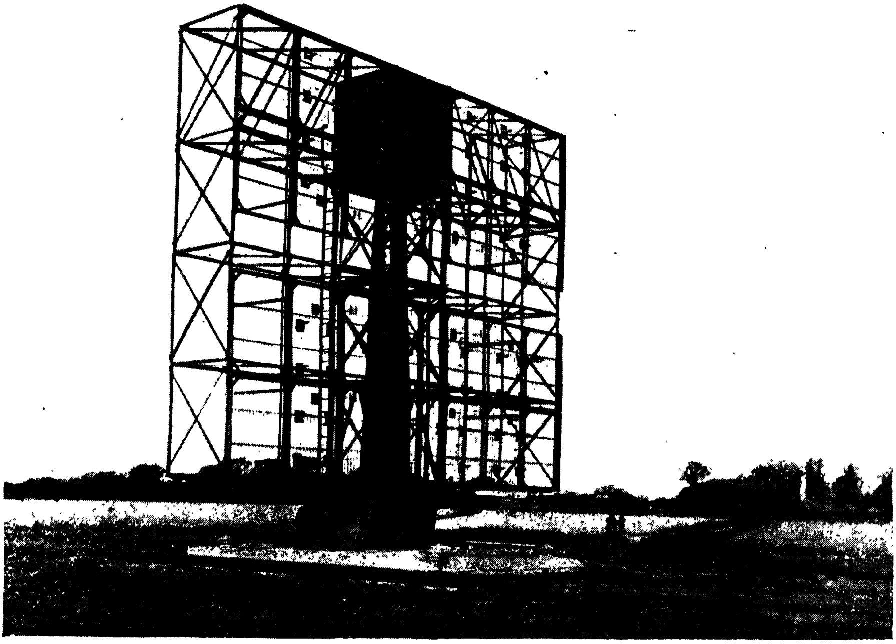
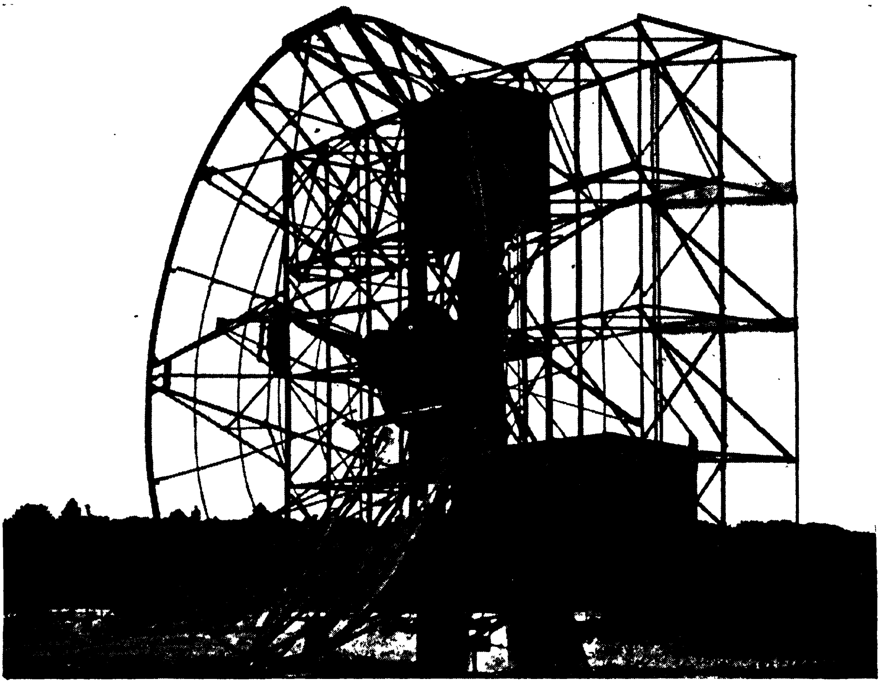


PLATE VI

The guiding of fighter aircraft to the enemy in the air by G.C.I. (Ground Controlled Interception) evolved, like other projects, as shorter waves became available. One of the earlier sets working on 1½ metres at Durrington is at A. Note the large aerial array which flings a somewhat broad beam. The kind of oscillograph display is shown at B. 50-centimetre waves were used in the Type 16 set, C, which had a narrow beam and used a P.P.I. (Plan Position Indicator) display on the oscillograph. Various other types of set were used later. D is a photograph of a P.P.I. tube showing the type of display obtained with a 1½ metre G.C.I. equipment. Note the aircraft responses at a, b, c, d, e. The remaining responses are due to permanent echoes from grounded objects. The aircraft responses are easily identifiable by the fact that they move from one rotation of the aerial to the next.



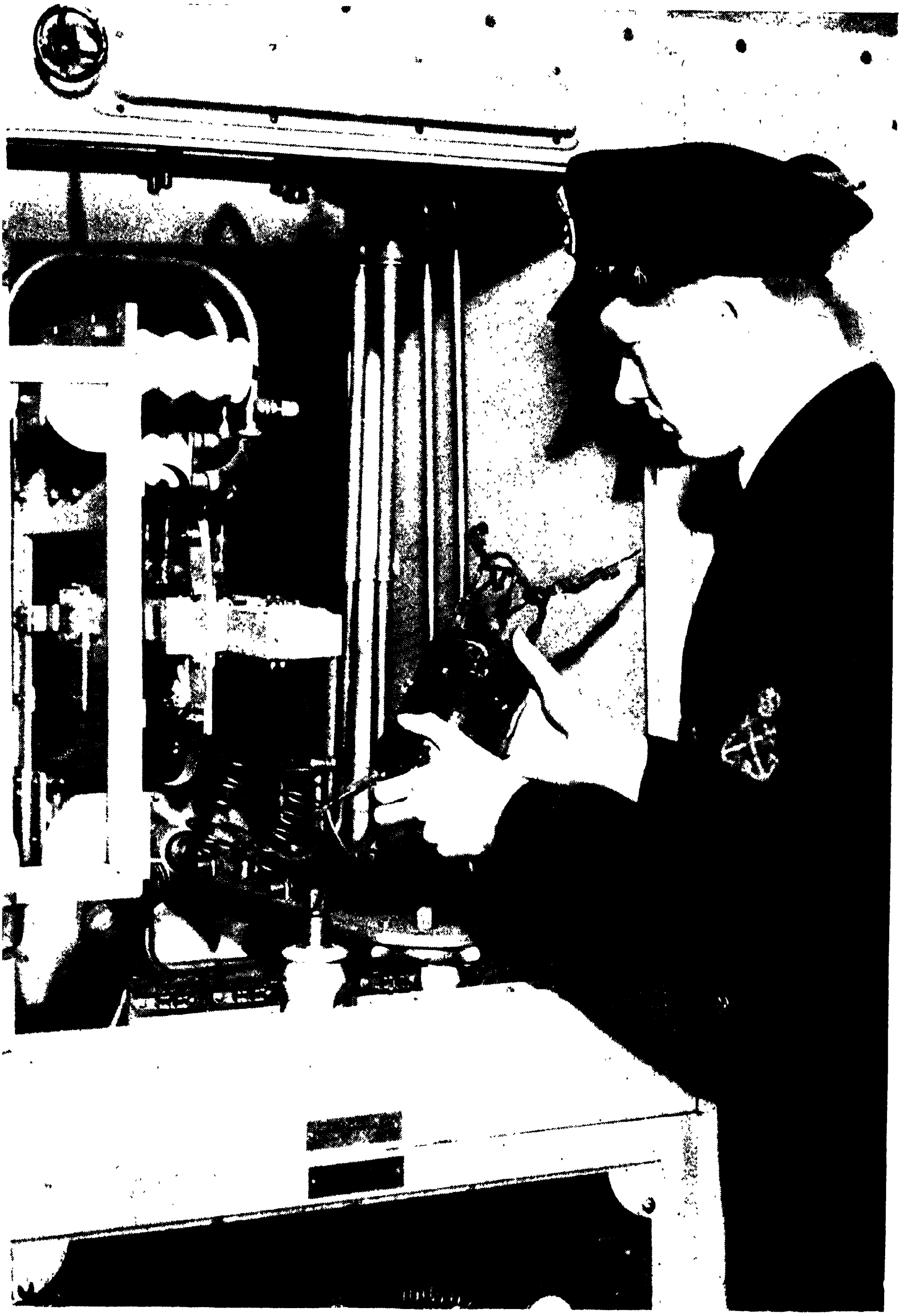


PLATE VII

A silica valve being inserted in the transmitter of radar type 281. This valve, of a type developed and made in large quantities in the Admiralty Signal School before the war—is made of glass which (like modern oven-ware) will resist an intense heat.

The anode (the basket-like structure which can be seen inside) is made of molybdenum, and when working is cherry-red hot.

The first chain of watching stations, which was ready in September, 1939, successfully detected the approach of enemy aircraft at heights of about 10,000 feet at distances of about 100 miles. It used waves of about 10 metres length emitted in pulses from high aerials. The echoes were displayed visibly on a cathode ray tube, and their direction determined by the methods which have been described.

DEFEATING THE LOW FLIERS

It has been explained that watching-sets operating on waves of 10 metres did not cover the lower levels of the atmosphere, and therefore were not adequate for detecting low-flying aircraft. A chain of special stations for watching the lower reaches of the air was added to the original system by the end of September 1939. Butement initiated this important development. These sets were able to use 1½ metre waves, owing to the introduction of improved radio valves. The shorter waves required much smaller aerial arrays and it was therefore practicable to mount them on a rotating turntable. They could be operated as a kind of radio searchlight scanning the horizon. The direction of the attacking aircraft was determined by finding the direction of maximum intensity of echo, as the " searchlight " swept round on its turntable one or more times per minute. The original watching system was static, and flooded the sky in front of the station with a widespread blaze of " radio light " : the additional system against low fliers using this rotating probing beam was called C.H.L. (Chain Home Low).

FIRST VICTORY

By giving an early warning against high and low fliers these two chains of home stations obviated the need for standing patrols of fighters, thus saving the fighter pilots' strength. Indeed, adequate standing patrols could not in any case have been provided owing to lack of a sufficient number of aircraft and pilots. Through the early location of the approach and place of the enemy the small number of fighters available were able to take off only when necessary, and then proceed to the very place where they were needed. In this way they intercepted the enemy with the minimum waste of effort, shot him down, and prevented him from attacking the fighter aerodrome and fighter planes on the ground.

The early warning system increased the efficiency of the use of the fighter force by an enormous factor. By this, and the blow it gave to the enemy morale through surprise, the Home Chain of

stations, known as C.H. and C.H.L., made a fundamental contribution to the winning of the Battle of Britain. The contribution to the defence of the civilian through the air-raid warning system was scarcely less great. Millions of men, women and children were given warning to take precautions, day after day and night after night, eliminating surprise and terror, and reducing danger.

The same warnings eliminated the need for thousands of crews to man anti-aircraft batteries continuously, thus saving strength and man-power, and providing rest.

HUNTING IN BLACK SPACE

The attack on Britain by day was beaten with the aid primarily of the 10 metre and 1½ metre watches whose elements have been described. This system determined the location of the enemy aircraft to within about three miles, and could guide the attacking fighter until the enemy aircraft was visible, in clear daylight, to the naked eye.

The enemy tried to evade the British fighters by attacking at night. Instead of attacking aerodromes and military installations, he decided to pour bombs on London and other great cities, to terrorize the population, and upset industrial production and civil administration.

So the night battle began.

During the daytime, to put the fighter pilot within three miles of the enemy bomber was generally sufficient. He could then pick up his quarry visually, and fly in to the attack. But this degree of guidance was quite inadequate at night. In the pitch dark of a moonless and hazy night no bomber could be seen by the eye beyond about three hundred yards.

It was necessary for the pilot to be guided to within three hundred yards of the enemy while the latter was still invisible to the pilot's eye. One part of the solution was to provide the fighter pilot with a portable radiolocation set, which he could himself use for locating the enemy in the dark.

Fundamental work was done by Dr. E. G. Bowen and his team at Bawdsey in the summer of 1939 on development of airborne radar equipment. They achieved the first flights with airborne radar, and the first 1½ metre air-interception sets were the result of their researches. The night battle of 1940-41 was won with these sets, after the design had been tidied up and the aircrews had been trained in their use.

The difficulty was that the equipment must be small in order to be accommodated in an aircraft, and would therefore, in general, be weak and of short range. The first set devised for this purpose had a range of about three miles. In order to keep the set small and light, the shortest waves that could be practicably handled at that time, $1\frac{1}{2}$ metres, were used.

Success with air-interception sets (A.I.) depended much on the users. The famous night-fighter pilot " Cat's eye " Cunningham had a scientific background. Dr. D. A. Jackson, the Oxford physicist, was one of the scientific observers who flew with him. They believed in their gear. These special pilots and observers were more like men working in a laboratory than ordinary air crews operating standard equipment. Jackson was so successful that he acquired the name of " 100 per cent Jackson." He is an ardent hunter and sportsman, and this seemed to assist him in forecasting what a hunted pilot would do, and thus keep him within observation.

How were the A.I. fighters to be guided near enough to the quarry from the ground to make their final contacts ? Special ground sets using special devices were devised and employed for this type of controlled interception.

Ground Controlled Interception

We have seen in a general way how a rotating beam probing the horizon can be set up. Such an arrangement gives direction and range (though not height) of an aircraft. But why not arrange for the time base in the cathode ray tube receiver in the rotary set to rotate in unison with the direction of the aerials on the turntable ? In that case, the direction, as well as the distance, of the aircraft would be immediately visible.

In Fig. 14 we have a representation of the face of a cathode ray tube. At the centre is a spot which starts coincidentally with the emission of a pulse, and moves at constant speed along a radius, faintly tracing out a time base. As successive sweeps by the spot are not made over the same line but over successive radii, a phosphorescent screen whose glow lasts for a long time after the spot has passed is needed. A screen with a memory, *i.e.*, a long " afterglow," was a necessary contribution towards the success of this apparatus—it was fortunately in existence, having been developed for other purposes. It is arranged that if an echo occurs, the spot momentarily increases in intensity, so that the trace of the echo lingers after that of the fainter tracing spot has faded out. Thus, with a number of different aircraft in the air together, each will be

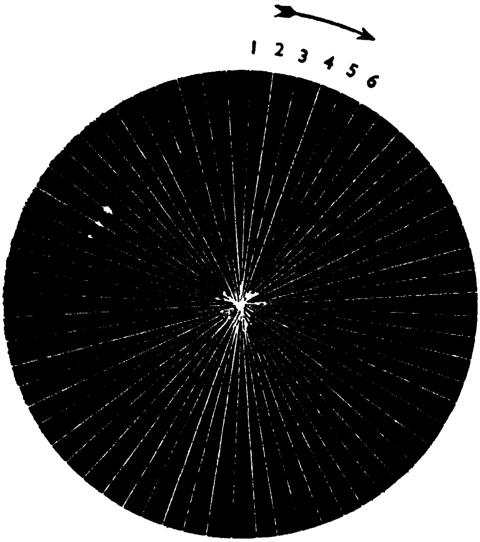


FIG. 14.—Radial Time bases on a cathode ray screen whose glow persists for some time. The radii 1, 2, 3, 4, 5, 6 are successive traces which start from the centre and travel to the outside of the circle when successive pulses go out. If an aircraft, e.g., at north-west, gives an echo, the spot brightens up on the screen and leaves a persistent mark.

represented by an individual smudge on the face of the screen (which is in effect a map of the sky for miles around the Radar tower) on which aircraft automatically mark their presence. The observer will be able to see not only the distance and direction of each aircraft, but also their relative positions. From the drift of the echo smudges on the screen, the speeds of the aircraft can be estimated. As the echo from each friendly aircraft will have an identifying feature, the observer can guide it by radio communications towards or away from enemy aircraft, as the case may require.

This arrangement, known as the Plan Position Indicator, presents the military commander with a moving picture of units in combat perhaps a hundred miles away. Once more, like the ancient heroes, the commander is able to see something of the situation at a glance, and act directly on his personal judgment.

Several teams working in industrial concerns as well as in Government Departments collaborated to produce the complete Ground Controlled Interception system. Bowen and Dr. W. B. Lewis and their teams of the Bawdsey research station; Mr. A. D. Blumlein and Dr. E. L. C. White of Electric and Musical Industries, Ltd. (E.M.I.) and their research staff; A. C. Cossor, Ltd.,

and their research staff, Dr. C. C. Paterson's research staff at the General Electric Company, Ltd. (G.E.C.), whose early valve pioneering work lay behind this and many other successful projects ; Pye, Ltd., and E. K. Cole, Ltd., who made up the earliest successful airborne radar equipment. This host of collaborators in a number of places evolved the airborne equipment.

In parallel with this, the ground equipment was developed from the pioneering apparatus of Butement, using (as before) G.E.C. transmitter valves, largely by Metropolitan-Vickers Electrical Company, Ltd., and Pye Ltd. Another host of names could be mentioned in this connection, too, amongst which we may include Mr. G. W. A. Dummer and Mr. J. A. Ratcliffe, whose team included Dr. Denis Taylor and Dr. Westcott. In naming this list many have been omitted, including the many flying officers and men of the R.A.F. who made the equipment work in this most difficult of operations—fighting in the air at night.

With improved guiding stations on the ground and better interception sets in the air, the night fighters became more and more successful. They shot down two enemy bombers in December 1940. In May 1941 their kills amounted to more than 100. The Night Battle of the Cities was won.

Even so, this system had grave limitations and it was not safe to rest on laurels, for example the reflection of the 1½ metre waves from the ground limited the range of a fighter's air interception set to a distance equal to his altitude so that air battles could not be conducted successfully at heights much less than 10,000 feet. Hence 10 centimetre waves, which could be focussed in beams quite clear of the ground, were urgently needed. This was one of the main causes of the drive for very short waves. Bowen and his team had prompted research on this problem as early as the spring of 1939. At Worth Matravers the scientists worked and continued to work on these problems of the ground controlled interception of night bombers which, as we have seen, required more refined methods than those which had proved so successful against day bombers. The door to success was opened with the invention and development of new short-wave valves.

OLD AND NEW VALVES

The Old Valve

The old radio valve contains two essential parts in common with the cathode ray tube—the cathode which, when heated, emits the electrons and the anode which serves to carry away the electron

current. The cathode ray tube has parts, in addition, which are not shared by the valve—such, for example, as the focussing shield for making the electrons travel in a very narrow pencil, the fluorescent screen on which the pencil writes, the deflecting plates which move the pencil over the screen. Nevertheless two essential basic parts in both devices are the emitting cathode and the anode.

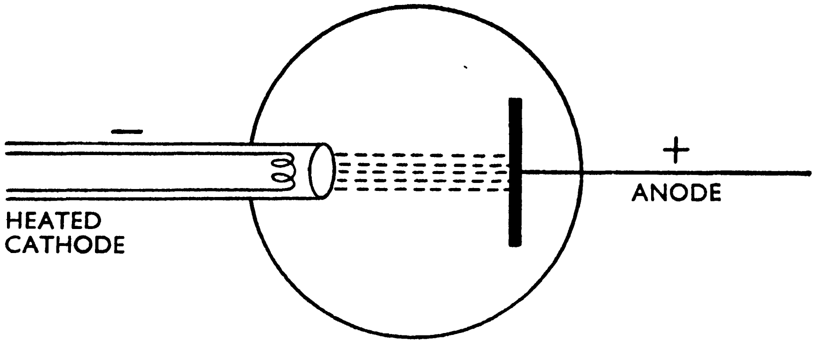


FIG. 15.—A beam of electrons, travels straight across the evacuated tube (a diode) from cathode to anode. It acts as an electric valve because by reversing the connections to the voltage supply no electrons appear, no current passes.

In Fig. 15 we have a diagram of a very crude form of cathode ray tube but with no deflecting plates. When the cathode and anode are respectively connected to the negative and positive terminals of a supply of direct electric current, electrons stream out of the cathode towards the anode. The material and temperature of the cathode are chosen so that electrons can escape from it particularly easily and a steady stream of electrons flows to the anode as long as the voltage is applied. Now suppose the voltage to be reversed ; the anode is not of the right material and temperature to produce a stream of electrons ; and the current through the tube therefore stops. The tube acts as a valve controlling the direction of the current through it since the current is let through only one way.

If into such a valve, a grid of wires is introduced, and placed near the cathode, the strength of the stream of electrons may be influenced. If the grid is given sufficient negative voltage, it may prevent the flow of any electrons from the cathode to the anode, and the cathode current will cease. By placing the grid very near to the cathode, the flow of electrons from the latter becomes very sensitive to the voltage on the grid. A small increase in the voltage on the grid produces a large increase in the flow of electrons from the cathode to the anode. Hence the magnitude of the current in the anode circuit is multiplied. In this way, the valve containing the

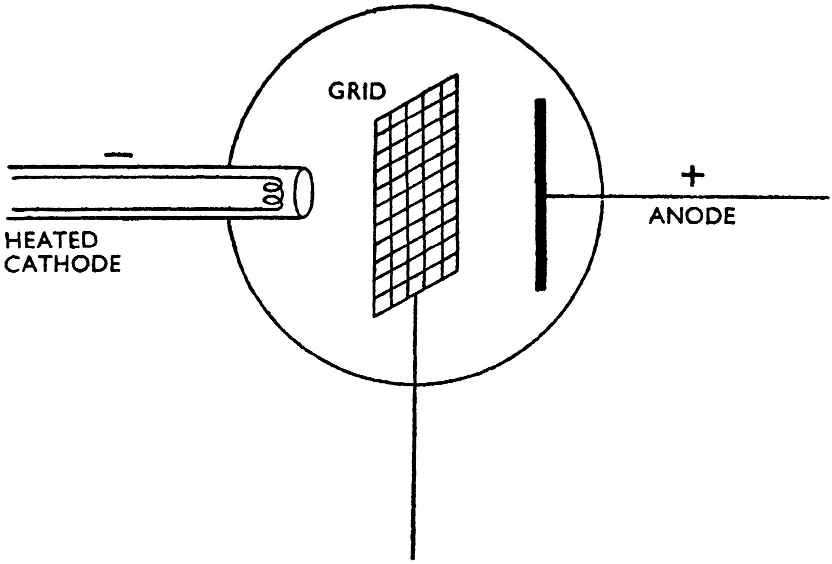


FIG. 16.—This is the "triode." In essence, this is the type of valve largely used in radar. A small voltage change on the grid produces large electron current changes in the valve.

grid, known as a triode valve, is able to amplify the effect of a small voltage applied to the grid.

This phenomenon is exploited in radio reception by attaching the receiving aerial to the grid of a valve, and securing from the cathode-anode current a greatly magnified effect of the very small current produced in the aerial by the received radio waves. By suitable adjustments of the various components, the receiving apparatus will be tuned to respond in the maximum degree to the particular length of radio waves falling on the aerial. It will be like a tuning fork or a piano string responding to a certain note.

It is easy enough to produce radio waves a few metres long by using coils of wire and electrical condensers in conjunction with radio valves. These coils and condensers act electrically in a way analogous to a swaying pendulum. In the case of a pendulum the bob swings to and fro and its swings are maintained by the clock mechanism which, drawing upon the energy of a coiled spring or poised weight, hands over a little of this energy at each downward swing of the pendulum, the function of the clock mechanism being to time these little impulses correctly. It it were not for these small successive and correctly timed impulses of energy the pendulum

would only continue to swing for a short while, its successive oscillations becoming smaller and smaller until finally the bob became motionless. So it is with the electrical analogue. An electric current swinging to and fro in the coil attached to the condenser will go on swinging so long as the mechanism represented by the valve and its coils continues to give appropriately timed impulses to the circuit, drawing on the energy of a battery or dynamo to provide the necessary power. Just as in the case of the clock we can make the pendulum swing faster and faster by making it smaller and smaller so in the electrical case we can make the electricity swing more rapidly to and fro by making the coils and condensers smaller. Up to a point, the valve which provides the timed impulses to the circuit continues to function successfully as the frequency of the oscillations increases, but a time comes when the frequency is so great that the valve can no longer follow them and for a reason which may readily be understood if the manner in which the valve works internally is considered for a moment. The valve operates in virtue of the fact that electrons, these tiny particles of negative electricity, are passing across from the central hot filament through the grid surrounding it, arriving finally at the outer anode. This flight of the electrons through the valve takes time, and the time taken for the electrons to travel between the filament and the grid is of particular importance. It transpires that even when the distance between filament and grid is only a small fraction of a millimetre, the electrons hardly have time to get across when the very high frequency corresponding to 10 centimetres is being used. This frequency after all is about three thousand million per second, and while it is true that special and extremely tiny circuits can be made to oscillate at this fantastic frequency, yet it is also true to say that sufficiently high power for radar purposes cannot in this way be successfully and reliably generated. Powers of many horsepower are necessary for modern radar, and it was not until the modern *cavity magnetron* was achieved that this became possible.

The Magnetron

The full story and underlying theory of the cavity magnetron cannot be told here. It is very complex and even at this present date the explanation, although known in broad outline, is not yet complete. The magnetron principle has been known for many years. Without going into inessential detail we may note that instead, as in the ordinary valve, of causing the electrons to move towards an anode under the influence of an electric field alone, we apply simultaneously a magnetic field in such a way as to make the electrons move not in a substantially straight path but in a curved

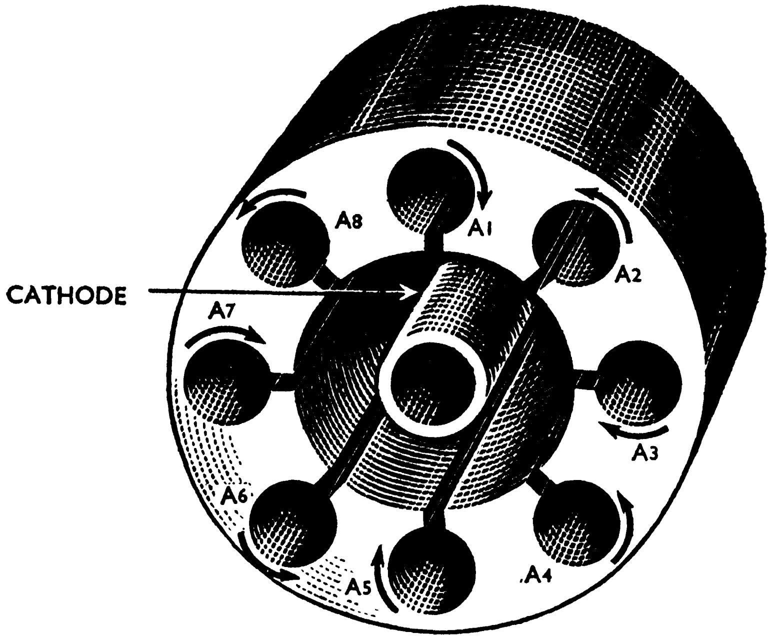


Fig. 17.—Showing the construction of the cavity magnetron.

one, so that they sweep out from the emitting cathode towards the anode—which some of them may not reach, if the magnet field is strong enough, coming back in such cases finally to the cathode. Thus electrons keep leaving and returning to the cathode at regular intervals, and if they are made to pass by suitably placed oscillation circuits oscillations can be maintained in those circuits. The point to notice in particular here is that tiny clearances are not necessary, as in triodes with grids. It occurred to Dr. J. T. Randall that this might be the best way to create very short waves. Of course magnetrons had already been made, of the then more or less conventional type, to produce short waves ; notably by the General Electric Company, Ltd. ; but their power output was inadequate and they were not particularly suited to mass production methods. But Randall, working with Mr. H. A. H. Boot in the Physics Laboratory at Birmingham University, was inspired to try an entirely novel type of magnetron which, on the second design, worked—and worked so well that it is literally true to say that for years no substantial variation from the original main lines was an improvement. A valve no bigger than a child's fist gave a reliable output—after much coaxing and care at the hands of the manufacturers—of hundreds of kilowatts in short pulses.

How was it done? It looks very simple in Fig. 17, which represents a block of copper with a large central hole turned out to leave a thick-walled hollow cylinder. In this cylinder and parallel to the axis are drilled circular holes with narrow slots opening out to the main inside hole. These holes and slots are as nearly equal as possible in every way. For our purpose it is near enough to the truth to imagine each hole and slot to be the equivalent of a tiny oscillating circuit—the slot being the electrical condenser and the cavity wall being a single turn of thick wire. The sizes chosen by Randall meant that each hole and slot could oscillate at the frequency proper to a 10 centimetre wave in space, *i.e.*, at 3,000,000,000 vibrations per second. If such oscillations took place in one of the holes, say A_1, some of its energy would at once be handed on to its neighbours until they were all oscillating in sympathy and it comes out that there is a curiously simple relationship between these currents when the magnetron is working on its best mode—for there are several ways in which it can work—and this relationship of currents is indicated by the arrows. At any instant neighbouring cavities carry currents moving in opposite directions—A_1; A_3; A_5; A_7 all swinging together; A_2; A_4; A_6; A_8 all swinging together but in opposition like the legs of a runner. This virtue of the octet of slots will now be obvious. A point to notice, too, is that very little of the radiation escapes from the holes or slots into the open air. This is one reason for the great success of this type of cavity magnetron. The energy is not wasted in useless radiation—having been built up within the cavities, all working together and simultaneously, it must be appropriately led out from one of the cavities by inserting a suitable probe or loop.

Down the centre of the main hole of the magnetron there is a large oxide-coated cathode heated by an internal spiral of wire and of course the ends are sealed with copper plates and the whole highly evacuated. The electric field is applied between the cathode and the outer resonator block—the latter being positive—while the magnetic field is applied, by a permanent magnet, in a direction parallel to the axis of the magnetron cylinder.

Very simple considerations show, as has already been said, that with appropriately chosen electric and magnetic fields the electrons fly out towards the anode and then back in variously curved paths. But very complicated computations indeed are necessary to bring out certain main points of great interest and we cannot do better than look at an actual diagram produced by the team working under Admiralty auspices at Leeds under the direction there of Professor E. C. Stoner, work which for some years was carried out in collaboration with another team at Manchester under Professor D. R.

Hartree. Fig. 18 shows what complicated paths some of the electrons pursue ; it shows also how the electrons bunch themselves up into clouds (of "space charge" as it is called) shaped exactly like a four-spoked wheel. This wheel is not at rest within the magnetron

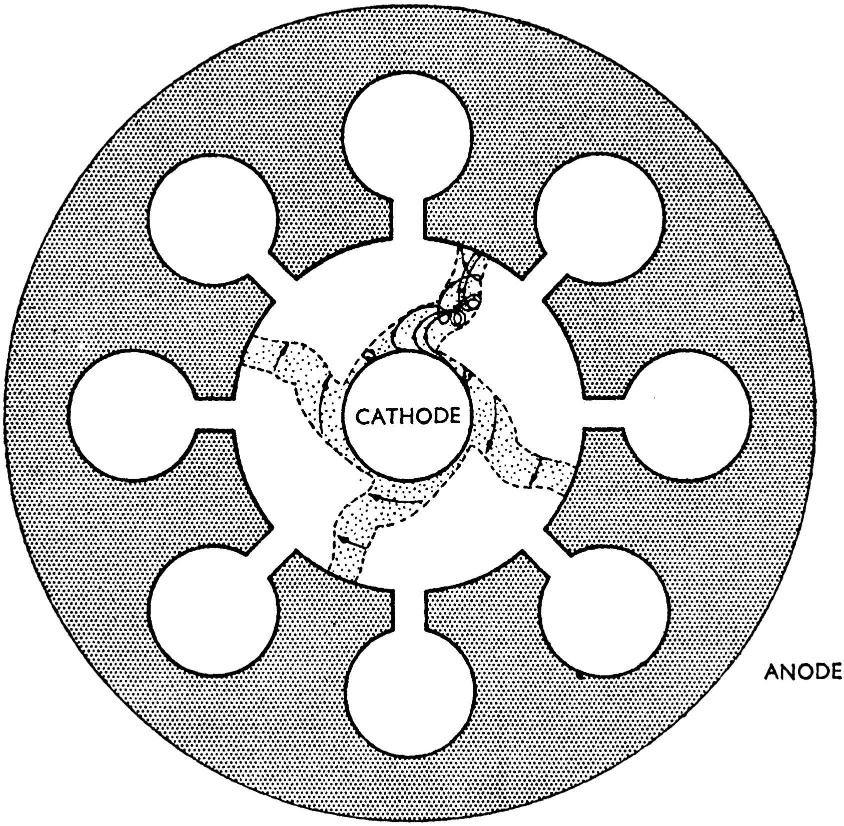


FIG. 18.—This is an actual copy of a diagram produced by a group of research workers at the University of Leeds showing the results of a laborious computation on electron distribution inside a magnetron at work. In this particular case the electrons bunch themselves up into a kind of four-legged cloud which races round in a clockwise direction, blowing a note, as it were, on each cavity in turn. Alternate sets of four are phased together. Note the curiously shaped paths of some of the electrons. Some reach the anode, others do not.

but whirls round at many million revolutions per second each spoke inducing oscillatory currents in the slots at the right instant to maintain any existing oscillations. It will now be clear that the magnetron works by a kind of siren action ; the rotating wheel of electrons blowing an electrical note, as it were, on the eight cavities within the valve. A similar principle governs the action of the klystron,

described on p. 41 and shown in Fig. 20. No one knew all this when Randall made his great invention, but this knowledge, obtained with painstaking and long continued labour, was of much value in understanding the processes within the cavity magnetron and guiding those designing new magnetrons at other wavelengths for other purposes.

With the complicated oscillatory possibilities offered by its construction the magnetron is apt to slip from the main mode of oscillation just described to other less favourable ones. A way of curing this is to strap alternate segments together with short pieces of wire so that they oscillate in phase, as in Fig. 19 ; an improvement introduced by Mr. J. Sayers at Birmingham.

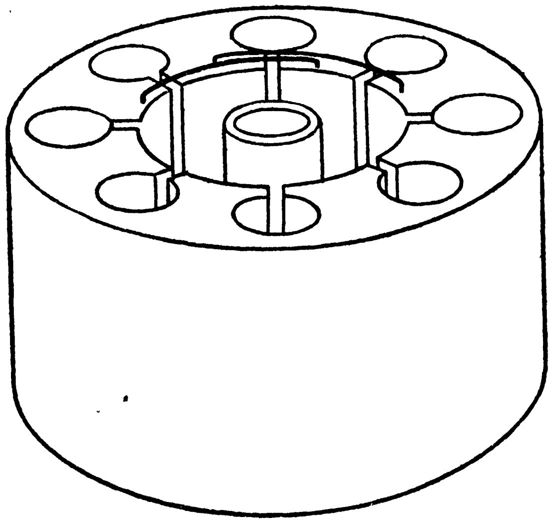


FIG. 19.—This is Sayers' Modification of the Randall Magnetron. It is the "strapped" magnetron. The curved wires or straps, of which only two are shown, keep the alternate cavities oscillating in step with each other reminiscent of the three-legged race action.

The first magnetron with a slot-and-hole anode set up by Randall and Boot was immediately successful, and produced nearly a kilowatt of 10 centimetre waves in brief pulses ; 100 times as much as could be produced from other valves. It was presently improved to work at more than 10 kilowatts, which was more than 1,000 times as effective as the earlier valves, and latterly at hundreds of kilowatts' peak output. In one of the forms most used in aircraft, it operated at 14,000 volts and 9 amperes, with a magnetic field of 1,350 gauss. It produced 9 centimetre waves and a pulse

of about 25 kilowatts for one-millionth of a second, about 1,000 times a second. The mean power is, of course, relatively small, 25 watts in the example—which compares with that of a low power electric lamp. The whole valve was only a few inches in diameter. The valve worked at about 70 per cent efficiency at its best and the early 8-cavity design has been improved on only in detail. It probably had a more decisive effect on the war than any other single new weapon.

What brought this great success ? A most important factor was the fresh consideration given to the need for very short waves by physicists from another field, Professor J. D. Cockcroft, Professor M. L. E. Oliphant, Lewis and others, who were brought in from fundamental research on atomic physics to consider the problems of military science, just before the outbreak of war.

People with such previous interests and knowledge had become acquainted with the practical problems of high power radio in the design of such apparatus as cyclotrons, in which enormous currents flow over large surfaces of copper. The main problem was to generate large power in short wavelengths but not high power continuously, radar requires it in very large supply for very short times—high peak power. The Birmingham group cast around for arrangements which would permit the association of large radio-frequency currents with adequate electron streams. The one obvious scheme to try was the magnetron, on which Randall and Boot accordingly worked. It was clear that the circuit must be within the valve and that currents must flow over broad copper surfaces. We have seen how Randall and Boot achieved this.

Industry deserves the highest credit for making this original magnetron from the laboratory into a sound reliable factory proposition. It took time. Soldered joints were taboo—therefore an existing but little known technique of joining copper plates together was used. A thin washer of gold was placed between the plates to be joined which were then held firmly together and heated until the gold diffused into the copper, so forming a tight indestructible joint. The original cathode was a tungsten wire ; more emission of electrons was wanted, which was supplied by a large oxide-coated cathode internally heated. A number of other important practical features were introduced. Mr. E. C. S. Megaw of the General Electric Company Ltd. had a leading part in turning the cavity magnetron into an industrial scientific product and the British Thomson Houston Company Ltd. also played no inconsiderable part.

The Klystron

The cavity magnetron was not the first valve to produce oscillations of such a short wavelength as 10 centimetres. Radiation of this wavelength had been produced, although only at small power,

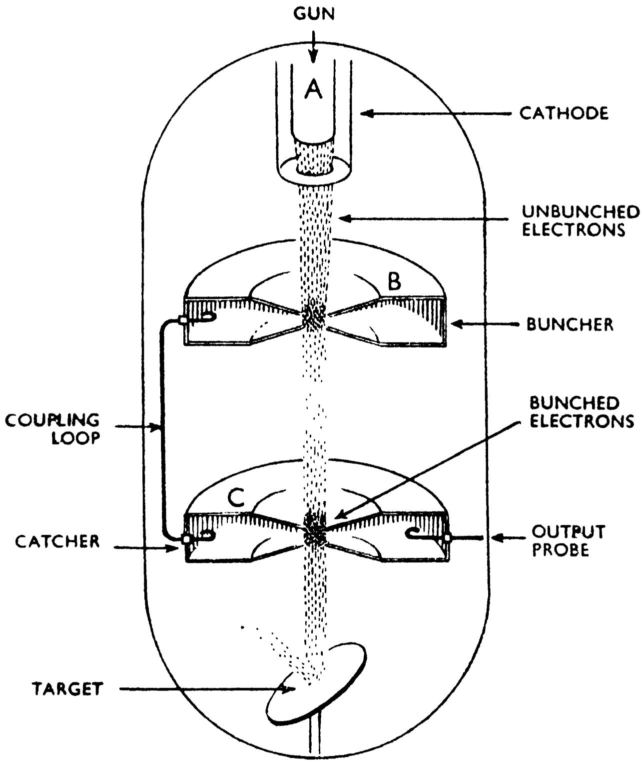


FIG. 20.—The picture shows broadly how a klystron works. B and C are exactly similar cavities, one of which can be slightly deformed for tuning. A fires a steady stream of electrons through B in which gentle oscillations start and are shared with C through the vertical wire shown on the left. The oscillations get rapidly more intense and build up a maximum value by the bunching action of B on the electron stream. This results in a regular sequence of concentrated electron clouds travelling downwards through C in exact accord with the natural frequency of C. A picture of such an electron bead is shown at the instant of passing through C. It has "materialized" there and will disappear after passing through to the target T where it is to be reflected aside. Each electron bead adds its quota of energy to the oscillations. The power is led out from the catcher by way of the probe shown on the right.

before the beginning of the war. This was done by a form of valve called the klystron which gets its name from a Greek word meaning " waves on a beach." It was not suitable for use in aircraft at the earlier stage of its development because it had to be continuously exhausted by a vacuum pump to give high powers.

This device is shown in diagrammatic form in Fig. 20, and it consists of three essential parts :—A the electron gun which, just like a cathode ray tube, fires a narrow beam of electrons down the axis of the valve. During its passage down the valve the beam passes through the closed metal box B of the special shape shown. A few centimetres further on its path it passes through an exactly similar metal box C. These boxes B and C are known as rhumbatrons, a word derived from the Greek " rhumba " meaning rhythmic oscillation. This device was a pre-war American invention and works in a way which can be understood in general terms quite easily without the use of mathematics. This is what happens : each of the little boxes B and C is capable of performing electric oscillations in the same way as the wireless aerial. The wireless aerial when in a state of electric oscillation has myriads of electrons which surge to and fro within itself. The stronger the oscillation the larger the number of electrons involved. But while they are in the state of oscillation the aerial emits wireless waves, it radiates. The tiresome man using an old-fashioned set next door, or even half a mile away, is audible on your receiving set when his aerial performs these antics. But in the case of the rhumbatron the electrons in the performance of their oscillations run to and fro *inside* the box which, being of metal, reflects back within itself any radiation and so the oscillations build up inside the box and do not escape. Now you will notice that in the diagram there are loops inside both B and C connected by the wire. By this means a little of the energy enclosed in box B is immediately transferred to box C, so that if B oscillates C does also and *vice versa.* Now the electrons arriving at B from A arrive in a steady stream, but in passing through box B they are acted upon by whatever electric force there may happen to be at the moment of passage. Remember that there is an electric vibration inside that box and sometimes it will impede the electrons passing by, sometimes it will assist their passage. When it impedes their passage the whole beam will be slowed up and the electrons will leave with a lower velocity. When it assists their passage they will be sped on to catch up the slower ones which went before. The cavity B is called the " buncher " and C the catcher. Thus between B and C (called the drift space), the faster electrons catch up the slower ones so that they arrive at C bunched closely together.

The process can be visualized by thinking of a handicap track race where the runners are started one after the other each according to his known prowess, the slower ones earlier, the faster ones later. A perfect handicap would mean all competitors reaching the tape together.

Reverting to the electrons it will be realized that the race between B and C is repeated a few thousand million times per second and run exactly to schedule so long as the klystron is oscillating ; the electron bunches hurtle one after the other in regular sequence like a string of necklace beads through the central hole in C in their passage maintaining a " note " of the right frequency in it.

This is because B and C emit, as it were, the same note and the beads have been strung out by B so that the box C (termed the " catcher ") will find itself in resonance with the cathode ray beam passing through it and so oscillation will be strongly built up, passed back to B which will produce still more vigorous bunching and so the process goes on until very strong oscillations are built up. The analogous action already mentioned in the case of the magnetron will come to mind. There, the "note" was "blown" by a rotating four-spoked electron-cloud "wheel," here it is blown by a moving necklace-like electron cloud ; in either case the speed of motion is a controlling factor. The klystron is thus seen to be a kind of cathode ray tube in which the cathode beam instead of being influenced transversely is influenced longitudinally.

The klystron is a difficult and tricky valve to make and use. The two rhumbatrons have to be most carefully matched together—a process so difficult that very tiresome and expensive manufacturing expedients had to be introduced. For example, in one form of klystron the rhumbatrons were made of flexible metal to form a vessel which could be evacuated—a clever scheme but tiresome and not robust enough for service use. The final solution was much cleverer and more practical. Only one rhumbatron was used. The electron beam went through it and was then sent back again over its course in reverse. The same rhumbatron acted as buncher and catcher. No tuning was required to produce oscillations, they automatically appeared—the wavelength adjustment necessary in actual use was made externally and in a simple way by altering the effective volume of the chamber. The valve is known as the " reflection oscillator."

The mode of construction of this valve is illustrative of a new technique developed for this purpose by the Admiralty Signal Establishment's team working as a unit within the walls of the Wills Physics Laboratory in the University of Bristol under the

charge of Mr. R. W. Sutton and with close contacts with the General Electric Company Ltd., and particularly Electric and Musical Industries Ltd. The new technique is called the copper disc seal technique and while developed particularly for these reflection oscillators has been of enormous value for other types of valve too. The scheme is simplicity itself (apparently!) and merely consists in melting glass tubes on to a copper disc in the manner shown in Fig. 21. The difficulties were in the early days entirely mechanical and were solved by choice of the right glass and right copper. The manufacturers at first did not care at all for the novel scheme but eventually made it work perfectly in mass production. It was a real winner.

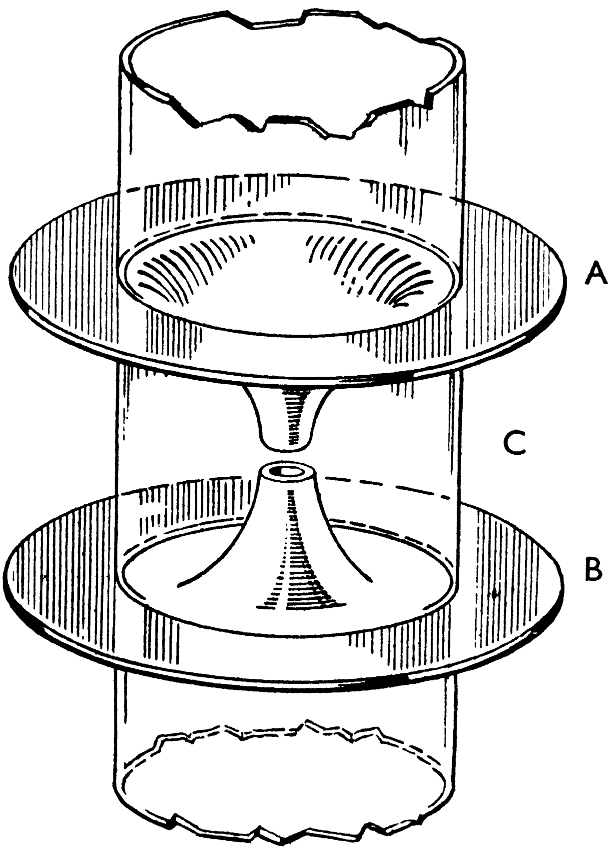


FIG. 21.—This illustrates one of the techniques which made modern valves (such as are shown in principle in Fig. 20) practical possibilities. It is the copper glass seal technique and one rhumbatron is shown but without the metal collar which must be clamped between the flanges to complete the box.

The rhumbatron was completed by clamping the edges of A and B with metal cylinders between them. Tuning was effected in the 10 centimetre oscillators by screwing large plugs in and out—a process which varied the effective volume and so the wavelength. The vacuum is " held " of course, by the glass tube C which is within the oscillating cavity at 10 centimetres. This works quite well but at the shorter wavelengths, for example 3 centimetres, the rhumbatron becomes quite small and the glass prevents the production of oscillations. The reason is just that glass absorbs the radiation of this high frequency rather strongly and introduces such heavy losses that the oscillations are inhibited. Special and more difficult structures, therefore, had to be used which we shall have to pass over with this bare recognition of their existence.

The reflection oscillator is as essential a part of the 10 centimetre radar set as are a magnetron and a receiving crystal. This trinity of new devices forms the essence of the whole set. The magnetron, oscillating at a frequency of 3,000,000,000 cycles per second, sends out a thousand pulses of energy per second, each pulse lasting for a millionth of a second (containing 3,000 wave crests). All the time, the reflection oscillator working at a frequency of say 3,045,000,000 cycles per second, is quietly feeding its continuous oscillations into the crystal. When an echo returns it is mixed in the crystal with the signal from the reflection oscillator and produces a " difference tone " of 45,000,000 per second which is then passed on to the amplifiers and after rectification finally to the cathode ray tube, where it appears either as a blip on a range trace or as an intensified spot on a Plan Position Indicator tube, according to the arrangement preferred.

Making the Valves

The first valves used in radiolocation were adapted from existing valves used for the continuous emission of waves. These were not particularly suitable for producing pulses. It was therefore decided in 1938 to increase the strength of the group working on valves under Mr. H. G. Hughes at H.M. Signal School (later, Admiralty Signal Establishment), and to secure the collaboration of the General Electric Company Ltd. in research and manufacture. The silica valve was much used in the early watching stations. During the Munich crisis there were not enough silica valves to keep the stations going, and the Signal School group had to turn all of their effort on to the actual production of valves.

More powerful valves for the stations with high transmitting towers were introduced in 1939. These were sometimes of the

continuously-evacuated demountable type developed by the Metropolitan-Vickers Electrical Company Ltd.

But the first valve specifically designed for pulse transmission, was the "micro-pup" valve, produced by the General Electric Company. It consisted of a copper anode which formed also part of the envelope, and it had copper-glass seals. This valve was much smaller than its predecessors, and enabled the first 1½ metre Air Interception sets in night fighters to work effectively. The big industrial problem of manufacturing this new kind of valve on mass-production lines was successfully solved, but these valves, though very valuable, did not meet the demand for very short waves at very high intensity.

In the Autumn of 1939, Oliphant at Birmingham and other leading physicists were asked to investigate the possibility of solving this fundamental problem. More of the electrical manufacturing firms were brought in, including Standard Telephone and Cables Ltd., the British Thomson Houston Company Ltd., and Electric and Musical Industries Ltd. The work was co-ordinated by an inter-service committee called the Co-ordination of Valve Development Committee under the Director of Scientific Research at the Admiralty and it operated through some seven sub-committees, sharing out the work appropriately between them. In this way, the research workers, the designers of radiolocation sets, and the industrial producers were brought together and became acquainted with each other's problems. The firms pooled their knowledge of techniques and freely exchanged secrets carefully guarded from outsiders.

Brilliant progress ensued. Randall and Boot produced their successful magnetron with slot-and-hole cavities, giving very short waves in powers of more than one kilowatt. The General Electric Company Ltd. then designed an industrial model, the first of which was produced in July, 1940. Then the British Thomson Houston Company Ltd. joined in, together with Hartree of Manchester, and Stoner of Leeds on theoretical aspects. Magnetrons were finally produced for all short wave applications, developing powers of hundreds of kilowatts.

The introduction of very short-wave radar through the magnetron immediately raised new problems of detection. The great development of the thermionic valve had tended, during the years, to imbue the radio specialists with a belief in the inherent superiority of valves for this purpose; however it was soon found that the old cat's whisker and crystal gave better results and the new demand for crystals led to studies of how they could be made more reliable and manageable. Both scientists and engineers agreed that it would be

far better, if possible, to double the performance of a set by improving the crystal receiver than by attempting the necessary very considerable power output of the magnetron. An improvement on the atomic scale, so to speak, would be the equivalent of a large engineering development.

Dr. H. W. B. Skinner, Mr. J. W. Ryde and Mr. T. H. Kinman led a combined research and industrial effort to improve crystal detectors and made robust forms which would be as reliable and easily handled as valves. This effort was assisted very considerably by the researches of the team at the Clarendon Laboratory, Oxford, where Dr. J. H. E. Griffiths and his colleagues contributed by making the necessary refined measurements on the crystals in their various forms, and in particular by testing their performance at the very much shorter wavelengths which soon became possible as a result of the development of the magnetron.

Ryde and his colleagues reviewed the properties of all known crystals from the short-wave point of view. It was found that silicon and tungsten were the most outstanding, but batches of silicon varied greatly from point to point on the surface. They began a systematic research on silicon. They sent a specimen to Professor G. I. Finch for examination by the newly developed technique known as electron diffraction. He showed that the crystal surface was covered with a very thin oxide layer. If silicon is cracked, the layer forms immediately, so they concluded they must produce a controlled oxide layer. They then found the silicon was not pure. They purified it by a method supplied to them by the National Physical Laboratory. Impurities in metals tend to settle along the crystal joints if the metal is cooled slowly, so they ground up the silicon so that all grain boundaries were exposed. They then treated them with a strong mixture of acids to dissolve the exposed impurities. The silicon was then fused and recrystallized and the process repeated. After this was done several times, the remaining silicon became fairly pure. Then the surface was polished to make it uniform. The polishing raises the temperature of the surface layer, which thereby becomes thicker. Bits of the polishing abrasive are left sticking in the layer. These were dissolved away with hydrochloric acid. So finally they secured crystals with a highly uniform surface. The cat's whisker gave signals of the same strength from all parts of the crystal immediately, and the crystal became as steady as a valve. They secured crystals with high burn-out characteristics, so that the same crystal could be used for long periods.

A brilliantly conceived ancillary device suggested originally by Dr. A. G. Ward, a Canadian working at the Telecommunications

Research Establishment, was swiftly developed by the Clarendon Laboratory team. The device is a crystal-protector. The first short-wave radar sets consisted of two concave mirrors, one containing the transmitting dipole and sending out many kilowatts of energy, the second containing the receiving dipole. Even with this separate arrangement of transmitter and receiver the crystal was frequently burnt out because of the considerable amount of current induced in it by its strongly radiating neighbour. It was therefore necessary somehow to protect the crystal. The same problem had already arisen in the longer wave sets which used receiving valves rather than crystals and a protection of the receiving valves was achieved by using an alternative spark gap device, not dissimilar to the lightning arrestors used to protect telephone circuits. While in the case of the long wave receiving valves a moderate degree of spark gap protection worked, a completely different order of protection had to be provided for the much more delicate crystal as used in the 10 centimetre receiver. An alternative spark gap would not do but it was found that a spark gap enclosed in a partially evacuated tube was much better, it was better still if tuned properly to the transmitter's signal. The final form was a cavity, tuned to 10 centimetre waves or whatever the length was, with a small pilot discharge or " keep alive " to help the gas discharge to start, and linked in a certain way to the receiving crystal. It was termed a "gas switch." It is interesting to notice why the "keep alive" is essential. The cavity, which is a replica of the rhumbatron described previously and is quite small, must always be ready for a discharge to start *immediately* the high voltage from the transmitter pulse arrives. It cannot instantly respond unless there are a few positively or negatively charged molecules at large in the space. In any ordinary discharge tube (a Neon sign for example) the occasional passage of a cosmic ray or radiation from the earth's radioactive content suffices and the short delay which may occur between switching on and lighting up is neither here nor there. It is otherwise with the gas switch, there must be the very minimum of delay, a supply of ions must always be waiting : this device was astonishingly successful and indeed made it possible even to use a transmitting aerial itself for receiving also. This greatly simplified the apparatus. As soon as the transmitter began to send out its pulse, even as powerful as hundreds of kilowatts, the protecting discharge tube came into action and adequately safeguarded the sensitive crystal. This crystal protection problem was not solved in its first form until June, 1941.

Using the new valves we have been describing, Skinner, Mr. (now Professor) P. I. Dee, Ward, Dr. W. E. Burcham, Mr. A. E.

Hodgkin, Mr. J. R. Atkinson and Lovell at Swanage in the Summer of 1940 erected radar sets with parabolic mirrors, with which they detected sheets of tinplate, boys on bicycles, men on foot, and all kinds of objects going down the " Centimetre Alley," as the path of this sharply-defined beam came to be called. Then they secured echoes from aircraft in flight, and even detected the periscope and conning tower of a submarine at four miles. With sharp beams, achieved by very short waves, a new era in radiolocation began.

A new group of workers of the Admiralty Signal Establishment was formed under Dr. S. E. A. Landale, and went to Swanage for six weeks to take advantage of this successful research. The party returned to the A.S.E. Extension at Eastney, with a replica of the Swanage laboratory apparatus. At the time, the problem of defeating the U-boats was very pressing, so it was decided to produce as quickly as possible a 10 centimetre set which could be sent to sea in a corvette, and used to reinforce the attack on the U-boats. This was done with outstanding success. The set, known as 271, was the first centimetre set to be used as a weapon in the war. Thus the Admiralty Signal Establishment has the honour of having introduced the first regular weapon using 10 centimetre radar. This was, perhaps, the Establishment's most brilliant contribution.

The A.S.E. had to design and make an aerial which could be trained on any bearing. It should be capable of giving a sufficiently concentrated beam to measure the bearing of a target with reasonable accuracy. Further, the set had to be used in a corvette which would roll heavily, so an arrangement would have to be devised to keep the radar beam on the surface of the sea, in spite of the rolling. Yet, again, the aerial had to be made or housed so that weather would not affect it. These problems were solved by designing a rotating aerial and reflector. The latter was cheese-shaped, giving a narrow beam in the horizontal plane, and a broader fan-shaped beam in the vertical plane. The whole was enclosed in a perspex lantern to give protection against the weather.

By May, 1941, components for 350 sets had been ordered, and by the end of July, 25 ships had been fitted, or were being fitted, with the set. Though not experts in mass-production, the scientists, engineers, mechanics and staff of A.S.E. contributed a great effort towards the making of these sets.

The destroyers protecting the convoys to Russia were fitted with "271," 10 centimetre sets for detecting U-boats. In the earlier part of the anti-submarine war these sets contributed more than the A.S.V. (Aircraft to Surface Vessel) sets, especially in the early months of

1942. In the middle of the Atlantic there was then a gap of 1,500 miles in the air protection of convoys, and in this region the 271 set was of particular value. Good radar warning sets were the weapon which made it possible to run fast merchant vessels, such as the *Queen Elizabeth* and the *Queen Mary*, for long distances without protection by men-of-war.

The new centimetre wave sets provided a new order of accuracy in the measurement of bearing and elevation, and provided a greatly improved method of aiming anti-aircraft guns at invisible aircraft. Formerly, in the day and night anti-aircraft batteries of 1940-41, gun-laying equipment working with 3½ to 5 metre waves had been mainly used.

It is worth noting that in these applications, the anti-submarine and the anti-aircraft, separate mirrors for transmission and reception could be used. In aircraft, only one mirror could be used.

Progress in radar was nearly always waiting upon improvements in valves. To meet this situation, the General Electric Company worked out a method of pre-production, by which small quantities of new valves could be produced by formerly unskilled women workers, while the problems of mass-production were being worked out. In this way, small numbers of sets could be produced quickly for exceptionally important operations. On several occasions in the war small numbers of sets were provided at critical moments with very great effect. In these "crash" programmes there was more difficulty in arranging to make the sets than the valves. Manufacturers found it very difficult to give up mass production, in order to make the 200 or so sets "off", which were often the war-winners.

Attack

A Debt to the Ancient Greeks

In the first years of the war, Britain was fighting primarily for survival, and her tactical effort was defensive. She defeated the air attacks of the enemy by day and by night, and she settled into a long and desperate struggle against the attacking U-boats. But her ultimate strategy was always offensive. She organized attacks on the enemy as and when she could muster the strength and aid.

As her bomber force was initially much weaker than that of the enemy, she was not in a good position to start an effective bombing attack. But after the air attacks on Britain in 1940, and with increasing air strength, more systematic bombing attacks on Germany were started. These were made at night, to evade the strong

German day-fighters and gunnery defences. They were continued year by year. It became clear, however, that in the first two years their effects were disappointing. The study of the effects of German bombing in Britain showed that bombing was much less destructive than had been supposed. Improvements in photographic reconnaissance showed that the actual destruction in Germany had previously been exaggerated, and intelligence agents brought reports showing that the bombing had apparently not affected the magnitude of German industrial production.

We began to appreciate that our bombs were capable of much improvement, that our early bomb-sights were relatively crude, and that our aircrews frequently failed to find even great cities, owing to inadequate navigational and identifying equipment. In fact, 90 per cent of the bombs dropped in the first two years of our bomber offensive had probably exploded harmlessly in the fields, and had had no effect. The total weight of bombs dropped in 1940 and 1941 was 44,737 tons. If only 10 per cent of these found their targets, it is evident that the effort had little military effect while costing much in valuable human life and skill, and in expensive aircraft. Owing to our isolation on an island, and our inferiority in man-power, direct invasion of Europe did not appear to be an early possibility. Hence, night bombing appeared to be our main means of striking directly at the enemy. If this should prove to be quite ineffective, our prospects would seem to be very poor indeed.

Most of those concerned were alive to the necessity of using the best navigational aids for night bombers and a special aid had been proposed by the scientists as early as 1938, an aid which had been accepted for development by September, 1940. It was a system which it was believed would put the bombers on the target with certainty. Thus, when in July, 1941, it was discovered that with no shadow of doubt our night bombing to that date had been really bad and wasteful, the new aid was very nearly ready and in fact service trials took place in August, 1941. These were so successful that a " crash programme " was commenced immediately, lasting until February, 1942, and actual operations using the new scheme began in March, 1942. It was a brilliant success. The need, of course, was to be able to find very exactly a target several hundred miles away in spite of darkness, cloud or fog.

How did the scheme work ?

The principle used may be illustrated by considering how you could reach a certain point on the opposite bank of a stretch of water covered in thick fog, without the aid of a compass. Imagine that you are stranded on the low bank of the lake, and that the

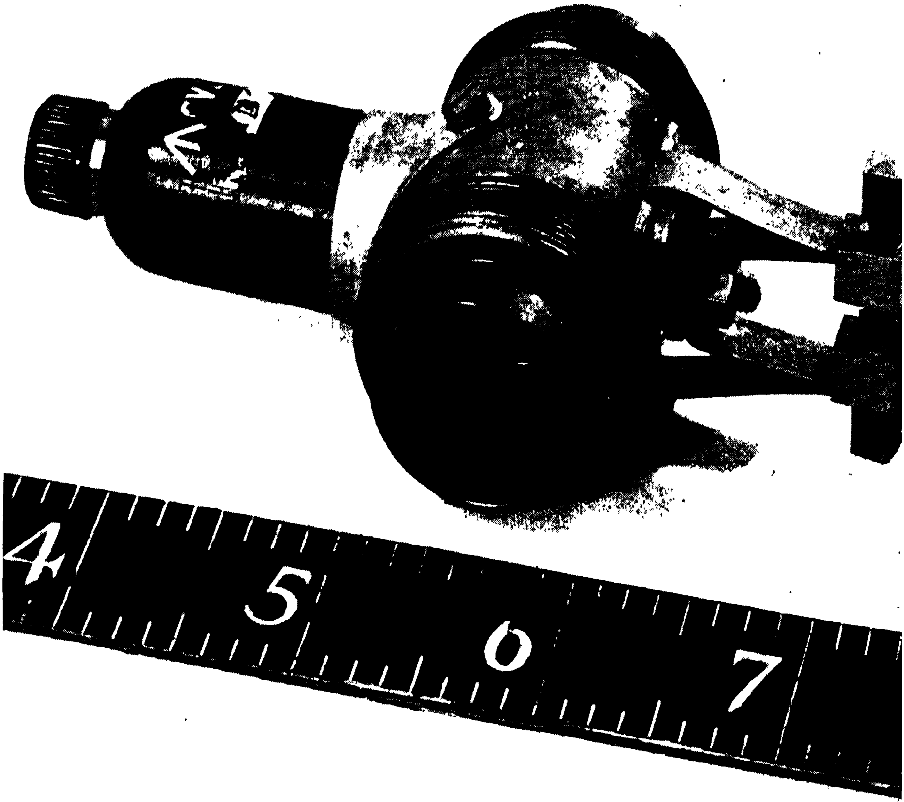
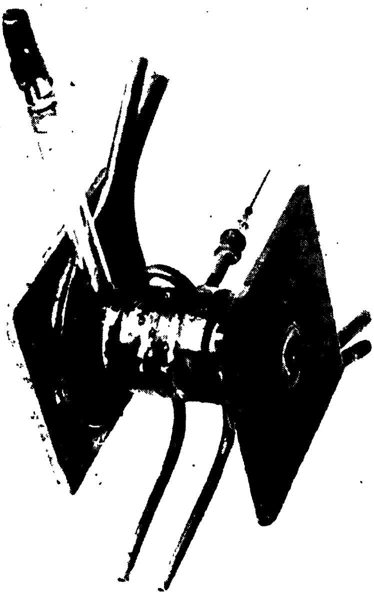


PLATE VIII

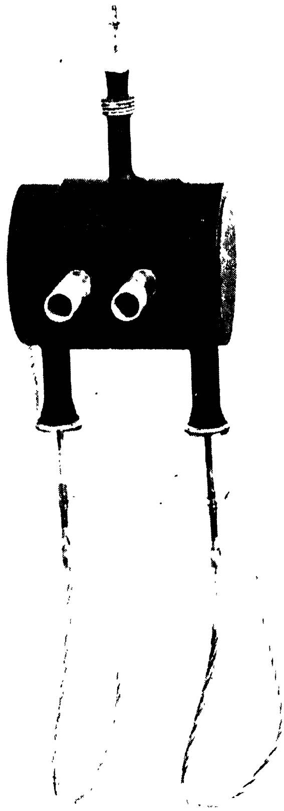
When very short waves—little more than an inch long, for example—are used in radar it becomes particularly convenient to use the same aerial (often a concave mirror) for both transmitting (T) and receiving (R).

The crystal must always be ready to receive an incoming echo, but being a sensitive device it is prone to be " burnt out " whenever the outgoing pulse leaves the mirror.

Incorporated in the transmit receive arrangement therefore—it is called a TR box—there is a device to protect the crystal during the transmitting periods. One form of this device is shown here. It is a small gas discharge tube, not unlike, in principle, the now familiar " neon " lamp, but very small and fitting into the wave guide or tube which leads the echo from mirror to crystal. This TR cell glows when too much power attempts to approach the crystal and functions as a protector. It easily passes small powers such as are associated with echoes but refuses to pass the higher transmitting powers.



B



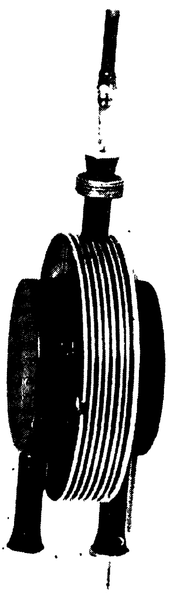


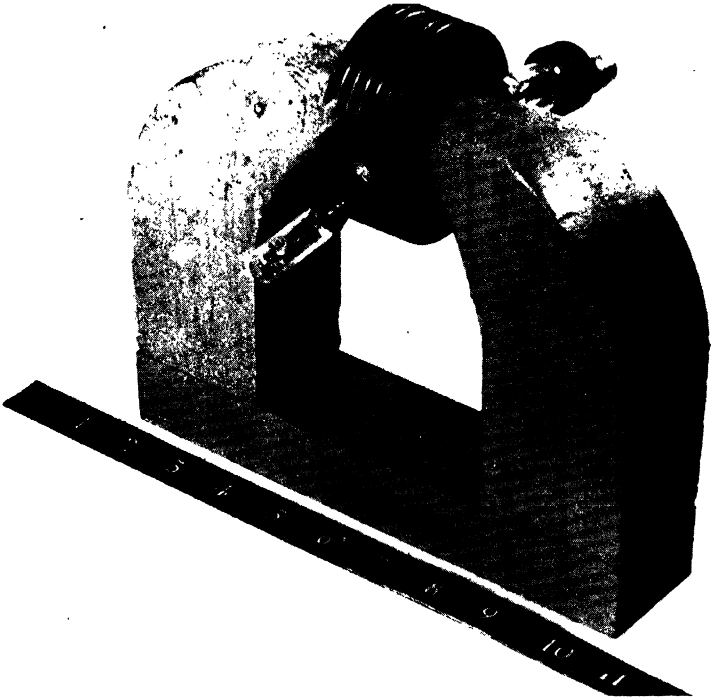
PLATE IX

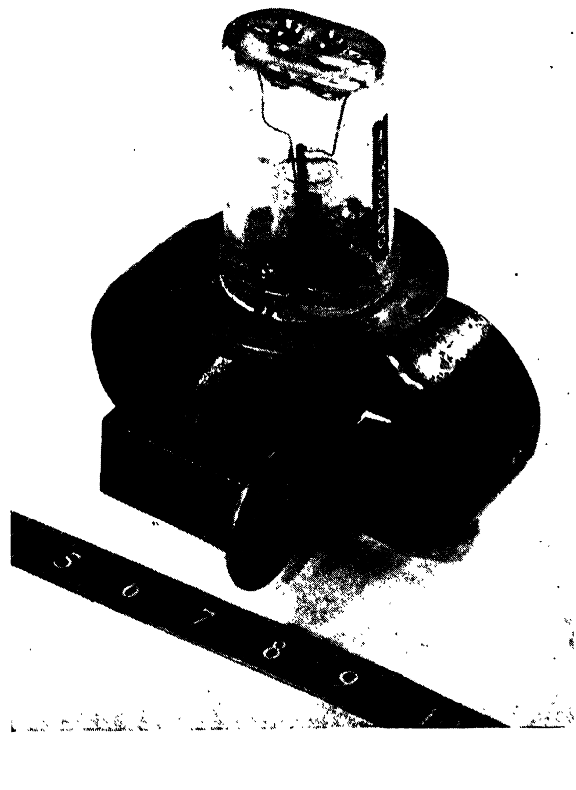
The Evolution of the Cavity Magnetron

A. After much effort at Birmingham University Physics Laboratory, Dr. Randall and Mr. Boot had made the first successful cavity magnetron by April, 1940, and sent it to the General Electric Company, Wembley, who very quickly adapted it to—

B. a neat industrial design. This was June, 1940. Note in both these cases the neat glass and metal seals and the water-cooling arrangements.

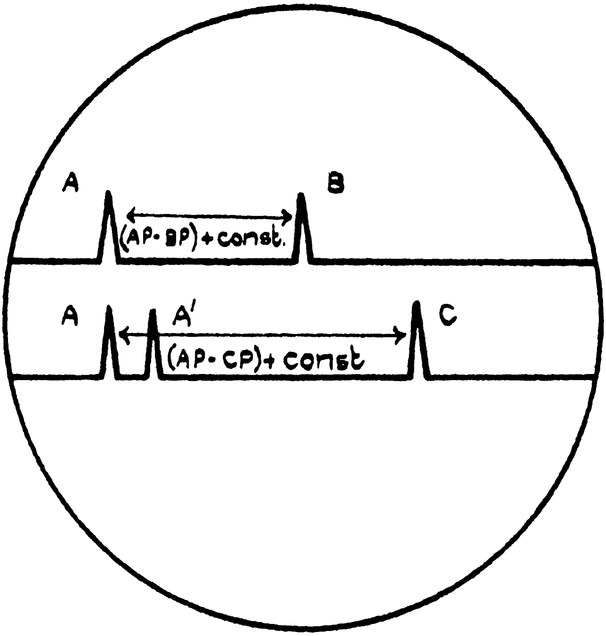
C. By the end of June the General Electric Company had produced an air-cooled design which used exactly the same cavity design but a greatly improved cathode. The pulse output was ten kilowatts as against the original half-kilowatt and the magnet, thanks to the co-operation of the magnet firms Messrs. Darwins, Ltd., and Messrs. Jessop & Sons, Ltd., now weighed only 6 lb.





D. The magnetron complete with magnet. These all operate at ten centimetres. Shorter waves than ten centimetres were on the way, and by 1942 a magnetron delivery power at three centimetres was available, mainly a joint effort by the Birmingham team and the British Thomson Houston Company at Rugby.

E. A late model ; it is a "package" with magnetron and magnet complete with rectangular wave guide out of which the power pours. A continuation pipe of any length required can be bolted on to the flange shown at the bottom of the plate.


A
B
(AP-BP)+const.
A
A'
C
(AP-CP)+const

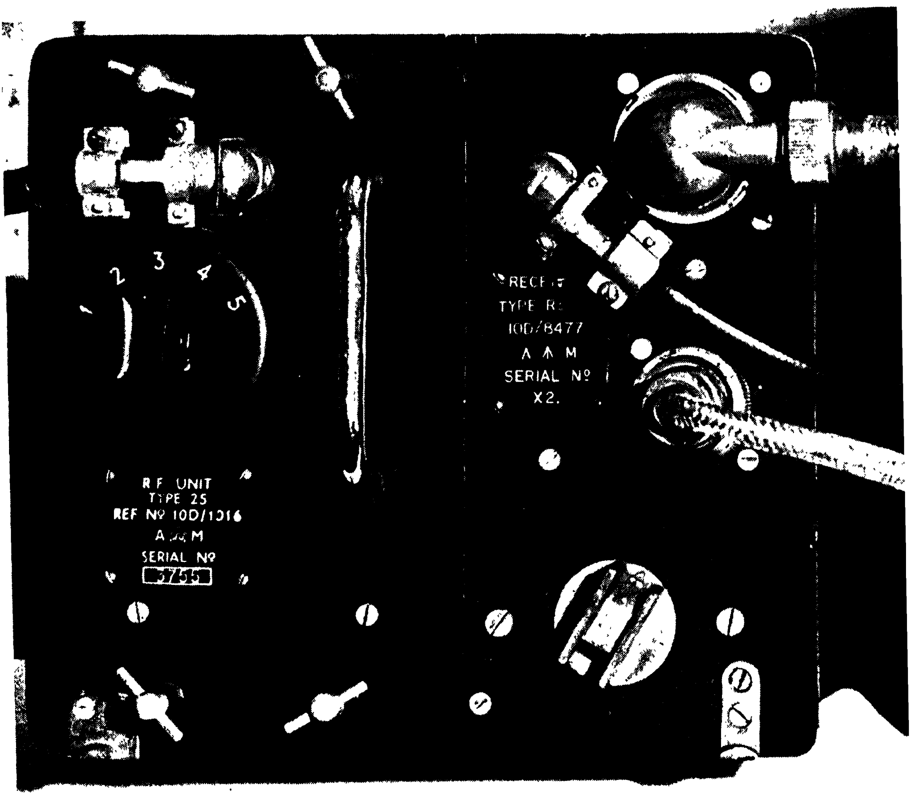
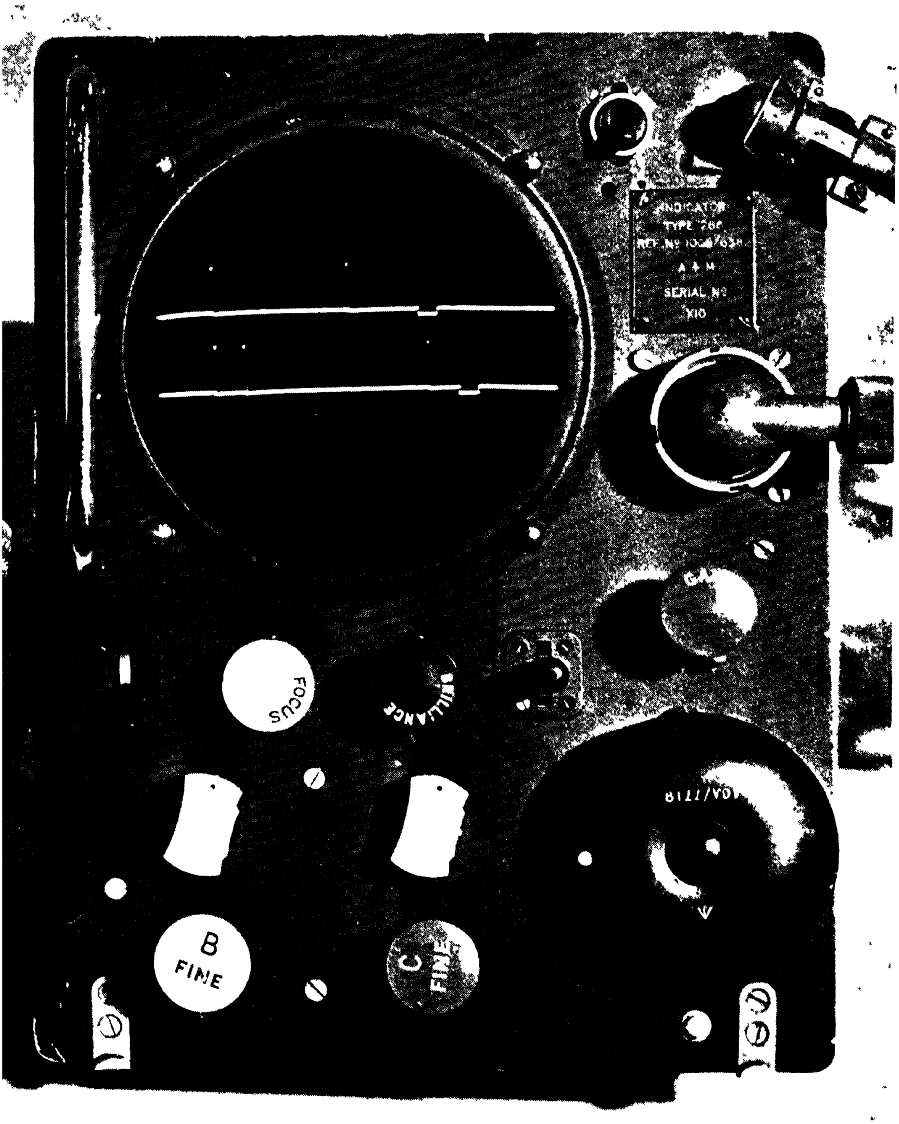

1
2
3
4
5
R F UNIT
TYPE 25
REF No 10D/1016
SERIAL No
10D/8477
SERIAL No
X2.

PLATE X

The two boxes shown here contain the essential Gee receiver used on aircraft; note the large knob (right bottom) which can adjust slightly the quartz crystal circuit which controls the electron sweep to one part in ten million or so. The two electron sweep tracks are shown (top right). The top line shows the (A) master blip and the (B) slave blip, while the lower line shows the (A) master and (C) slave. The third blip A shown on the lower trace is an identifying one, or ident, which differentiates the C from the B trace. Actually the same electron spot makes both traces, sweeping alternately on the upper and lower levels, 250 sweeps per second on each.

Referring to Figure 25 in text, the lettering corresponds and the blip C measures the distance (AP—CP), while the blip B measures the distance (AP—BP). The pilot then knows his precise position even when hundreds of miles from home.



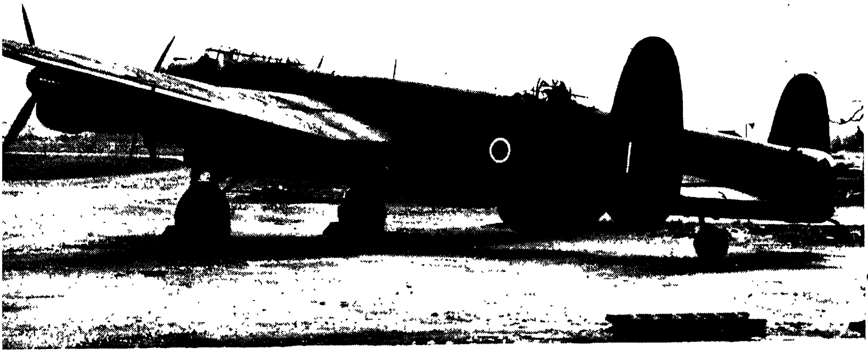
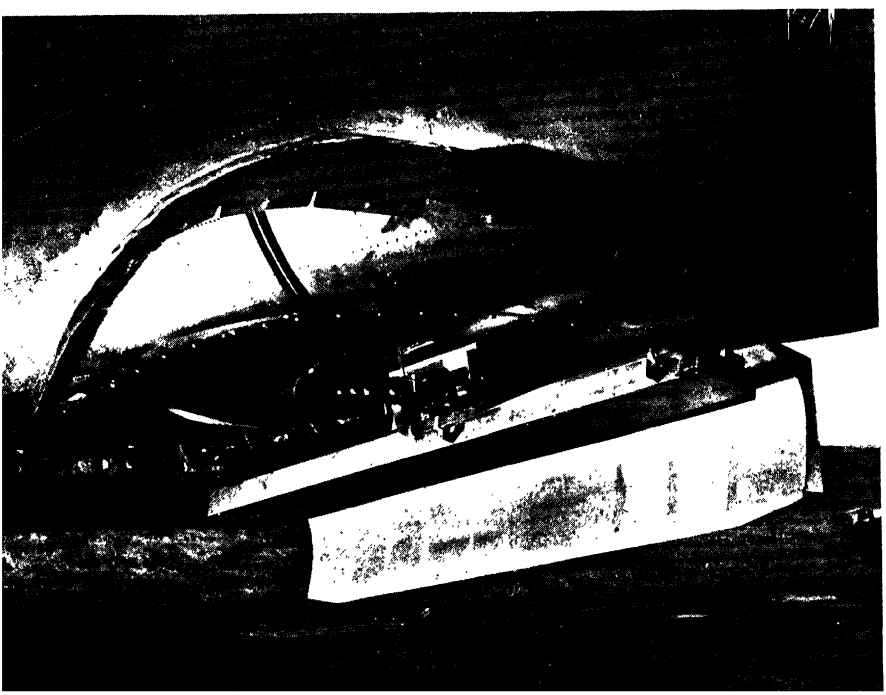


PLATE XI

The Perspex blister of a Lancaster bomber, containing the H_2S scanner, is seen on the under side of the aircraft below the rear turret.

PLATE XII

The Perspex blister under a Lincoln aircraft has been removed to show the large revolving scanner of an H_2S equipment. A twisted rectangular tube is seen coming from the interior of the fuselage. This is a wave-guide, which leads a stream of ultra-short waves to the aerial behind the rectangular base. These are focussed into a beam by the large reflector, rather like that on an electric fire. The arrangement, aerial and reflector, rotates as a whole in a horizontal plane, throwing a conical beam downwards, that sweeps over a circle of the ground below.



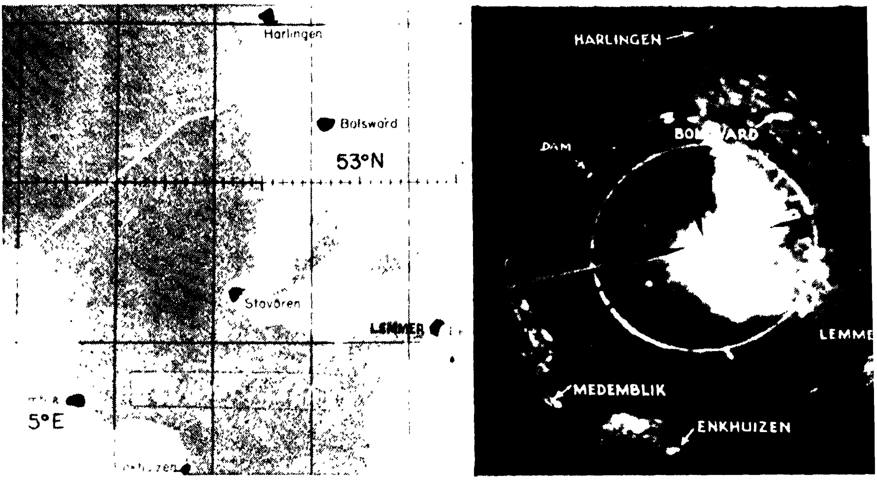
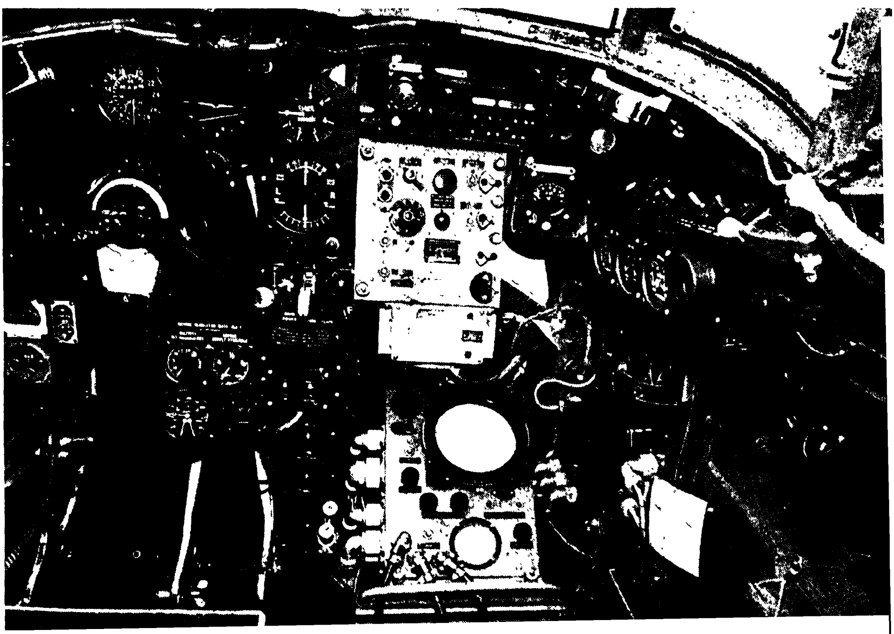


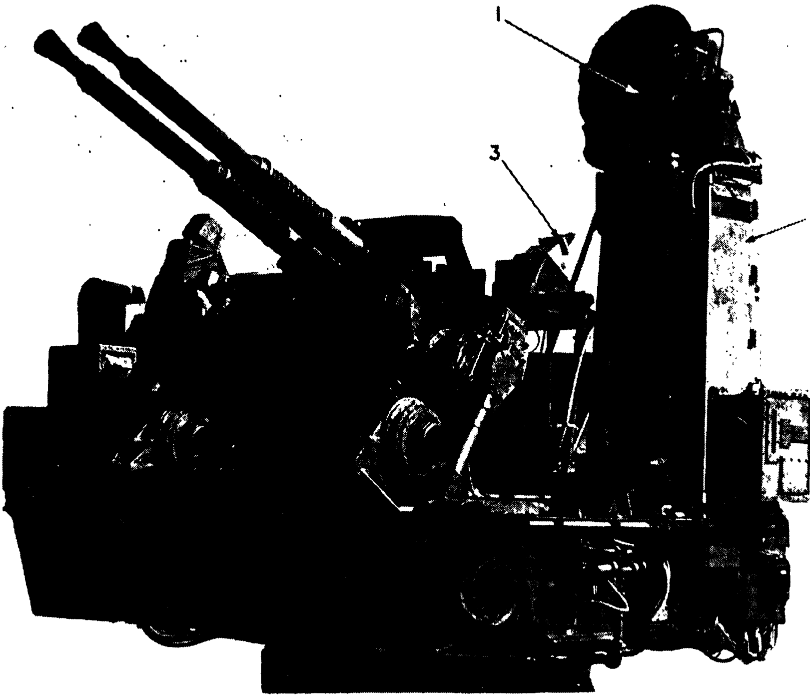
PLATE XIII

This " H_2S " picture of the dam across the Zuider Zee is fairly self-explanatory. It is taken with scanning apparatus working on the principles indicated in Figs. 31 and 32. The apparatus is carried on the aircraft and the scanner radiating through its down-looking Perspex blister receives the ground reflection picture on its cathode ray screen. The central part of the picture must be neglected but outside of this the radial traces are clearly seen—weakest where water reflects, or rather doesn't reflect, strong where land is below, strongest when there are buildings.

PLATE XIV

The H_2S equipment in a Mosquito aircraft. The face of its cathode ray tube is almost in centre of the picture. The complicated array of apparatus which confronts the present-day air crew is evident in this picture.





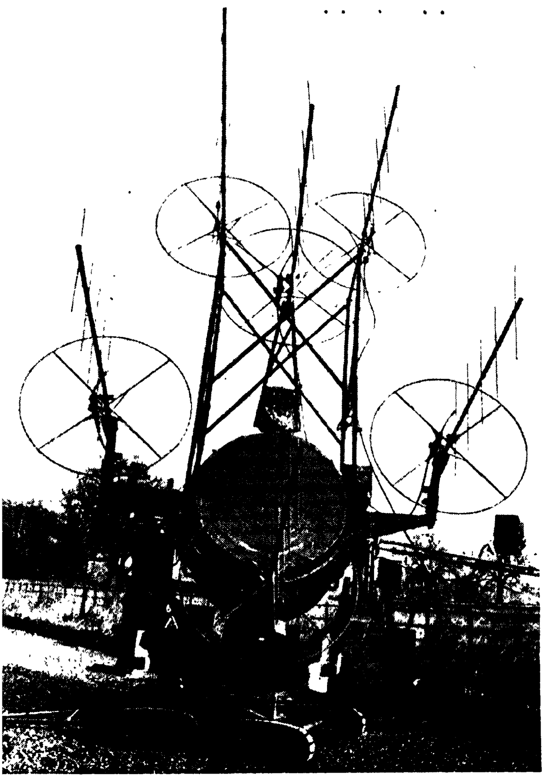


PLATE XV

A centimetre-wave radar, mounted on a twin Böfors gun-mounting. The dish-like aerial (1) is fixed to the top of the water-tight cubicle (2) which houses the radar gear. When a target has been found, the radar set follows the target automatically. The movements of the aerial are communicated to a predictor which moves the guns so that when fired the shells and the target will arrive at the same point in the sky.

PLATE XVI

An early example of a searchlight directed by radar equipment for spotting enemy bombers at night and revealing them to anti-aircraft gunners and R.A.F. fighters. The Yagi aerials (*see* Fig. 11) serve for transmitting and receiving. Two operators are needed, one for elevation, the other for bearing. The whole arrangement was named " Elsie."

other bank rises as a cliff from the water. There is one point where steps have been cut in the cliff, and this is the only place where you can land, and climb up to the open country at the top. You have only a boat, two large balls of string, and a map. How can you

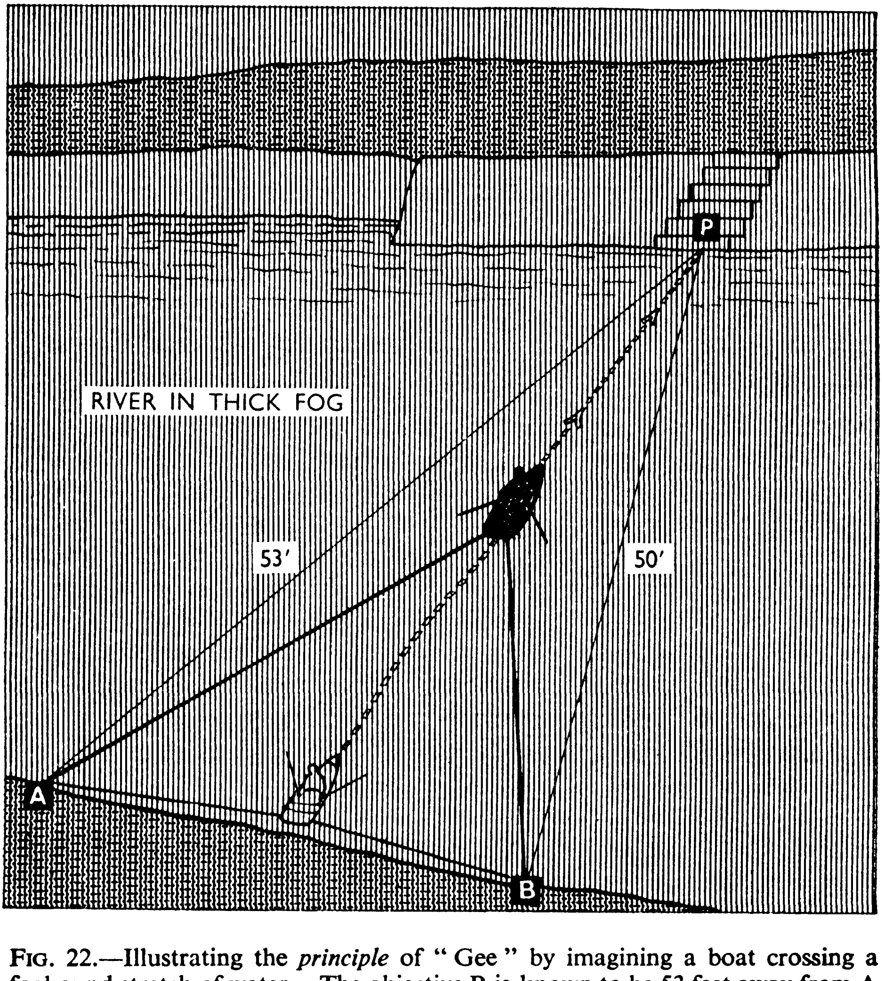


FIG. 22.—Illustrating the *principle* of " Gee " by imagining a boat crossing a fogbound stretch of water. The objective P is known to be 53 feet away from A and 50 from B. The cox therefore pays out two balls of string keeping them tight and the length on the A side always three feet longer. It is not claimed to be a very practicable operation but gives the idea !

row across, landing exactly at the bottom of the steps, which, owing to the fog, you cannot see ? You look at the map and mark the bottom of the steps as point P. Then you pick two features, such as posts, on your side of the river. You mark these A and B.

From the map you read that the distance from A to P is, say 53 feet, and from B to P 50 feet. You tie the end of one ball of string to the post A, and the end of the other to post B. If you now push off from the bank into the fog, you will know that when you have paid out 53 feet from one ball, and 50 feet from the other, you will be exactly at the bottom of the steps, though you may not be able to see more than a foot or so through the fog.

When you start on the voyage you will know that you must pay out three feet more from the ball attached to A than from the ball attached to B. You know that if you keep the difference between the lengths constant at 3 feet you will ultimately reach the bottom of the steps exactly. At the start of the voyage the boat will wander a little to one side and then the other, but by about the point D, you will have got into the hang of it, and will be easily keeping the string to A just 3 feet longer than that to B by paying out equally from the two balls. From D to P, you will keep the difference virtually constant.

Thus every point on the track of the boat from D to P has the characteristic of being just 3 feet farther from A than from B. The track forms a curve of a kind about which much has been known for a long time. It is one of the kinds formed by slicing a cone and is known as a hyperbola. The first man to write a treatise on hyperbolae (and other sections of cones, such as ellipses) was Menaechmus, the great Greek mathematician who flourished about 350 B.C. and was mathematical tutor to Alexander the Great. One day Alexander, perhaps after finding sections of cones confusing, as you may be finding them now, and as many navigators of aircraft have no doubt found them recently, asked his tutor to make the explanation easier. Menaechmus gave the famous reply that though in the country there are private and even royal roads, yet in geometry there is only one road for all. The new aid to navigation that the scientists proposed made use of the property of the hyperbola which we have just described. It guaranteed the accurate navigation of large numbers of aircraft simultaneously, and made possible the 1,000-bomber raids, and a new order of intensity of aerial attack. Thus Menaechmus, who found no royal road to the understanding of mathematics, did bequeath knowledge that helped blind-flying bombers to find a more-than-royal road to their targets through darkness, cloud and fog ; and whereas Alexander drew on his tutor's knowledge to conquer the world, the bombers set out on their hyperbolic paths, using the same man's knowledge, to strike down tyrants.

Geometry by Radio

The Greeks used strings to draw conic sections : we can even use wireless waves. Suppose now that we wish to guide a bomber

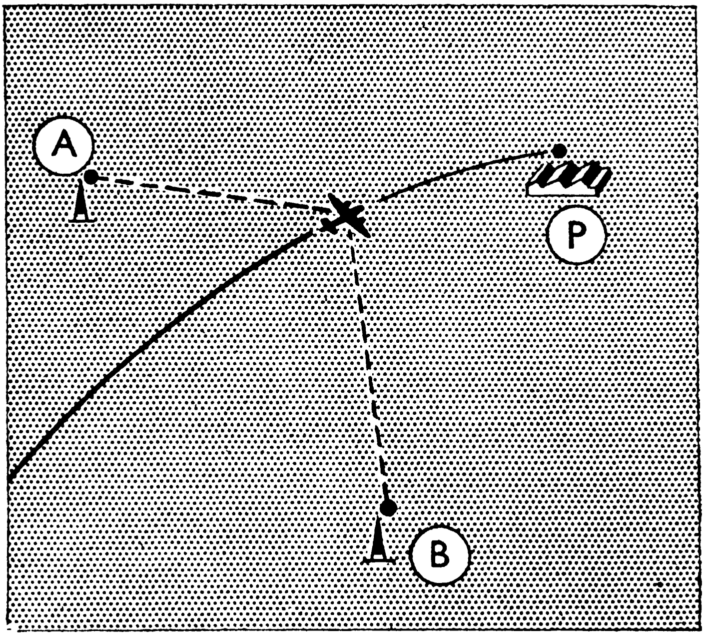


Fig. 23

through darkness and cloud to a specific target P, as in Fig. 23. From our consideration of the water-crossing problem, we see that all we have to do is to keep the aircraft on a path passing through P, such that the difference in the aircraft's distances from A and from B is always equal to AP minus PB. How can the pilot know that he is flying so that the difference between these two distances is always constant ? He cannot trail huge balls of string. He can, however, use the new techniques developed for radiolocation. If radiolocation pulses are emitted simultaneously from A and B, they will arrive at P at different times, because BP is shorter than AP. If the moments of arrival of the two pulses are recorded on a cathode ray tube in the aircraft, the distance between the two " blips " will be proportional to the difference in time taken by the two pulses to cover BP and AP respectively. Hence the distance between the two " blips " will be proportional to the difference in the distances of the aircraft from A and from B

respectively. Hence, to keep to the target curve path which will pass over P, the navigator has to direct the aircraft so that the distance between the two blips on the cathode ray tube remains constant, and corresponding to the difference in length between AP and BP.

The determination of the moment when the aircraft is exactly in the right position to bomb the target can be made with the help of a second pair of stations sending out simultaneous pulses. Suppose we have pairs of stations, A,B ; D,E. Then the curve corresponding to A and B will be H_1, and the curve corresponding to D and E will be H_2. The navigator can keep the aircraft on the curve H_1 and then announce the moment for bombing when he sees from a cathode ray tube that the aircraft has reached the point where the difference in distance from E and D is equal to EP minus DP. He will then know that the aircraft is on both paths H_1 and H_2, and must therefore be exactly at their point of intersection ; that is, at P. The two sets of hyperbolas are drawn on his guiding map in red and green respectively, for ease of reference.

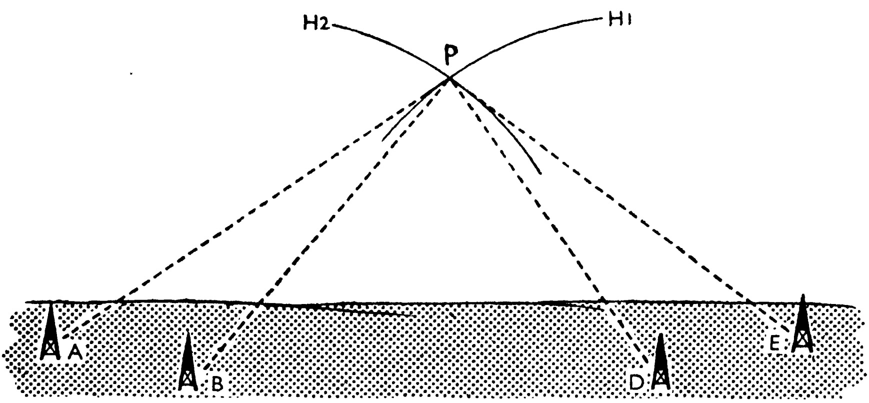


FIG. 24.—Though strictly speaking not radar, since echoes are not used, this method of position finding uses some of the Radar techniques. The diagram shows two pairs of pulse emitting stations AB and DE. Each pair emits a simultaneous brace of pulses from which the aircraft, using a cathode ray tube methods, can select those hyperbolas which intersect accurately over its objective. Parts of such a pair of hyperbolae H_1 and H_2 are here shown. This is "Gee" in principle.

Owing to the use of a chart covered with a network or grid of curves, the system was given the code name of Gee. It was invented by Mr. R. J. Dippy and developed by his team at Tele-

communications Research Establishment. In practice three stations are actually used. *A master station* A sends out a series of pulses. If we consider one of these, it will travel past station B, and also to the aircraft P and beyond. It is arranged that when the pulse reaches B, which is called a *slave station*, a transmitter is then activated which issues a second pulse. A second pulse from A also activates a transmitter in a second *slave station* at C. Then the cycle repeats.

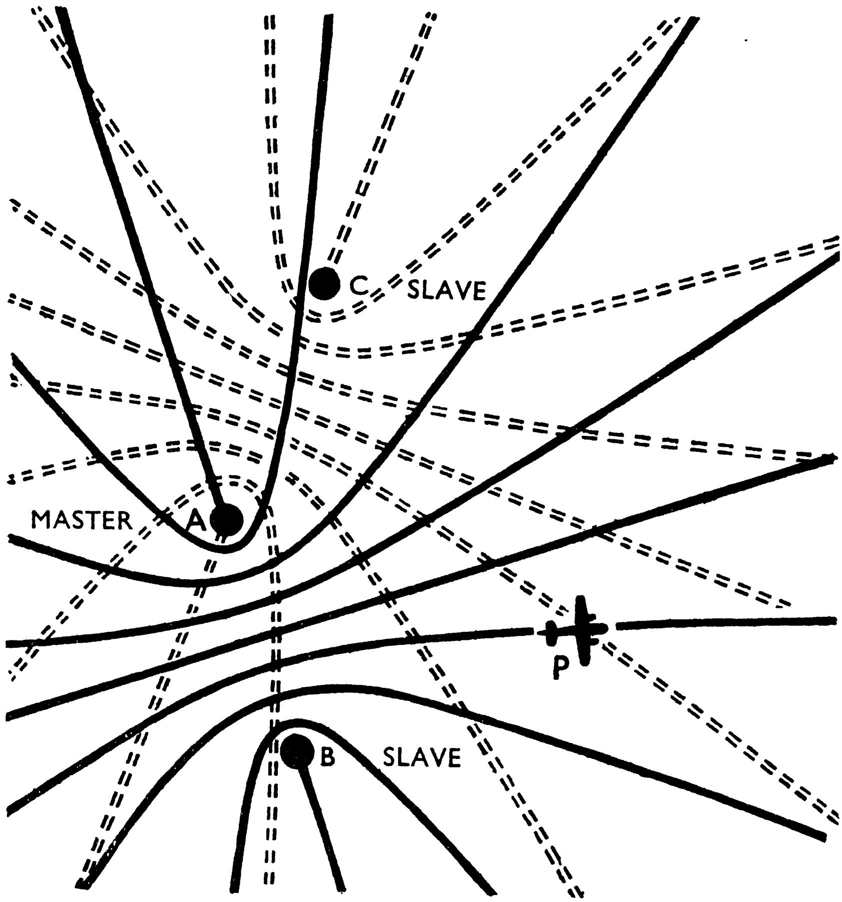


FIG. 25.—This figure elaborates Fig. 24. A is a master station controlling the slave stations C and B. The navigating aircraft is at P. A can activate C or B at will. By using its cathode ray tube instruments the aircraft can feel its way among the radio hyperbolae choosing the correct pair of intersecting ones for its navigational purposes.

The aircraft carries one cathode ray tube on which the arrival of the four pulses is recorded. The navigator is provided with a

chart covered with two intersecting sets of curves, corresponding to stations A and C, and A and B respectively. This can be superposed on a map of the country to be flown over. The target is marked on the map, and hence its place in respect to the curves is seen.

From the places of the four blips on his cathode ray tube, the navigator is able to read at once where the aircraft is in the net-work of curves, and give the pilot the appropriate data to guide him to the intersection of the two curves which mark the exact position of the target. It will be understood that an aircraft need not necessarily fly down one of the curves and the right one at that, in order to reach his target, although this was the line taken for ease of exposition. He can always tell from his instruments on what hyperbola he happens to be and set his course accordingly.

This system can guide hundreds of bombers simultaneously to a target, to an accuracy of about 2 miles in 350 miles, and bring them home to their bases to within about half a mile. It eliminated the need to guide homing aircraft by signals to each of them from the ground. This would have needed hundreds of separate signals in a large raid, leading to confusion of messages.

It brought the large scale targets of the Ruhr within accurate range, and provided the condition for its destruction. The first big Gee raid was made with 350 bombers on the night of March 8th, 1942. About one-quarter of the aircraft carried the new equipment, and acted as fire-raisers. The raid was highly successful compared with previous attacks. On May 30th, 1942, aircraft equipped with Gee led the first 1,000-bomber raid on Cologne. The leaders arrived on time and started vast fires in the middle of the target. Then the following aircraft bombed at exact intervals for ninety minutes. All of the guidance for the hundreds of aircraft was given from just three stations, one master and two slave, in England.

The Navy adopted the Gee system in the Summer of 1942 for guiding its craft in all weathers in the English Channel. Coastal Command aircraft employed it for guiding them in their anti-U-boat attacks. Finally, the navigation of the aircraft employed in the invasion of Europe was mainly based on this system. The aircraft carrying air-borne troops were guided by Gee to their exact place for dropping their troops ; the bombers which blasted the enemy beaches and defences were guided by Gee ; and after the landing, a chain of Gee stations was established to guide our aircraft accurately into the depths of Germany. In fact, Gee played such a notable part that some have said that D-day should really have been called Gee-day.

Radar Guides who tell you where you are when asked.

For still more accurate navigation very much modified forms of this system have been developed. In one of these, the aircraft carries a pulse transmitter. On the ground are two fixed radio beacons which immediately respond to a pulse from the aircraft, each emitting another one that returns to the aircraft for display on its cathode ray tube receiver.

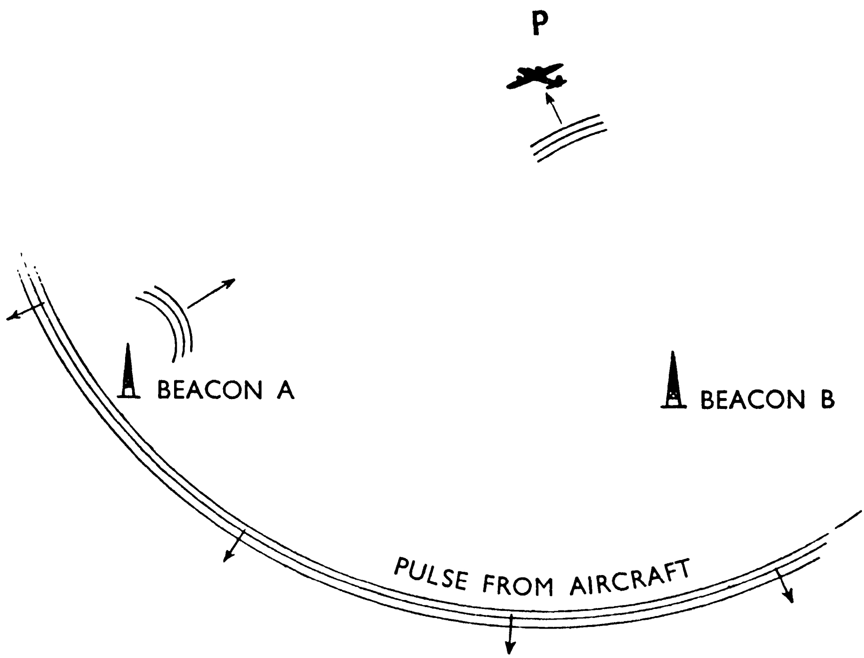


FIG. 26.—Another position-finding system in which, however, the aircraft "interrogates" by sending out pulses. The Beacons A and B "respond" that is, return very strong echoes, which the aircraft receives. From the display of these echoes on its cathode ray tube the aircraft determines its position accurately.

When a pulse emitted by the aircraft P in Fig. 26 is received by A, a fresh pulse immediately returns from A to P. Similarly, from P to B, and from B back to P. The two return pulses from A and from B arrive at different times according to the difference in distance between P and A, and P and B. From these two times the distances PA and PB can be calculated directly, and from a knowledge of the three lengths PA, BP and AB, the place of the aircraft can be determined to a high degree of accuracy.

This system gives an accuracy of one yard per mile, or 200 yards

at 200 miles. It enabled single factories in the Ruhr to be hit by blind bombing. It was used with great effect against flying-bomb and secret weapon sites on the Continent, and with it the headquarters of the 21st Panzer Division was annihilated in an attack a few days after D-day.

Bombing without Knowledge of Path, Place or Time

Yet another high-precision method of radar navigation removed the necessity for the pilot to find the target or even know where he was going. All of this could be managed from ground stations without the knowledge of the pilot, who was relieved of much strain and decision, and could devote the whole of his attention to the controls of his aircraft.

In this system (see Plate XXIX), there are two fixed stations, A and B. Station A enables the aircraft P to fly along the circumference of a great circle, whose centre is at A, and whose circumference passes over the target C. This station, which pushes the aircraft this way and that, tracking it, as it were, and making it keep to the circle, is called the Cat station. The stations A and B send pulses which are picked up by the aircraft, magnified and returned. From these responses, the exact distance of P from A is recorded at A, and of P from B is recorded at B. The *Cat* station emits a signal as a result of its knowledge of the distance PA. If the aircraft has strayed to the right, so that AP is greater than AC, the pilot hears a series of Morse dashes in his earphones. If the aircraft strays to the left, too near to A, he hears a series of dots. But if he keeps exactly on the circle he hears a high-pitched continuous buzz. The *Mouse* station B watches the aircraft, ready to warn it when it reaches the target and should, as it were, dart down the hole. It gives the pilot a series of warning signals as he comes within range, and then a final signal at the right moment for releasing the bombs. It may even release the bombs without the pilot's intervention at all.

The inventor of this system, called Oboe, was Mr. A. H. Reeves. Like Dippy and Lovell in their developments of Gee and H_2S, he worked in close collaboration with Group Capt. (now Air Vice-Marshal) D. C. T. Bennett, the Pathfinder leader, who tried and adopted it. It was used by Pathfinder aircraft to mark special targets, which could then be attacked by following bombers.

The first ground stations used for operations against the Ruhr were near Dover and Cromer. From these on December 21st, 1942, Pathfinders were guided for the first time to Krupp's works at Essen, with brilliant success. From then onwards, the town and factory areas of the Ruhr were found with steadily increasing

PLATE XVII
Destruction in Hamburg after the first major attacks led by H_2S, in July, 1943.

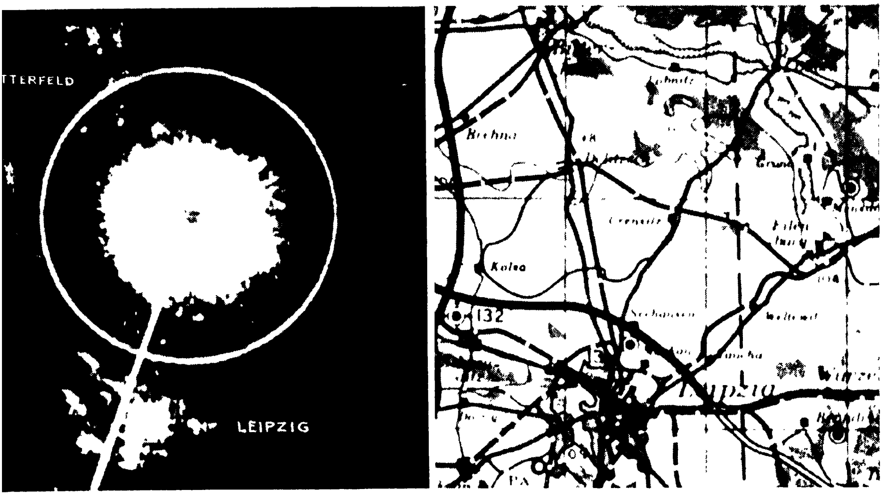


PLATE XVIII
An early H_2S photograph of Leipzig (*see* Page 69).

PLATE XIX
Leipzig burning after the attack of December 3rd, 1943. This was a bombing attack through 10/10 cloud marked by H_2S.

PLATE XX
Destruction in Leipzig after the attack of December 3rd, 1943.

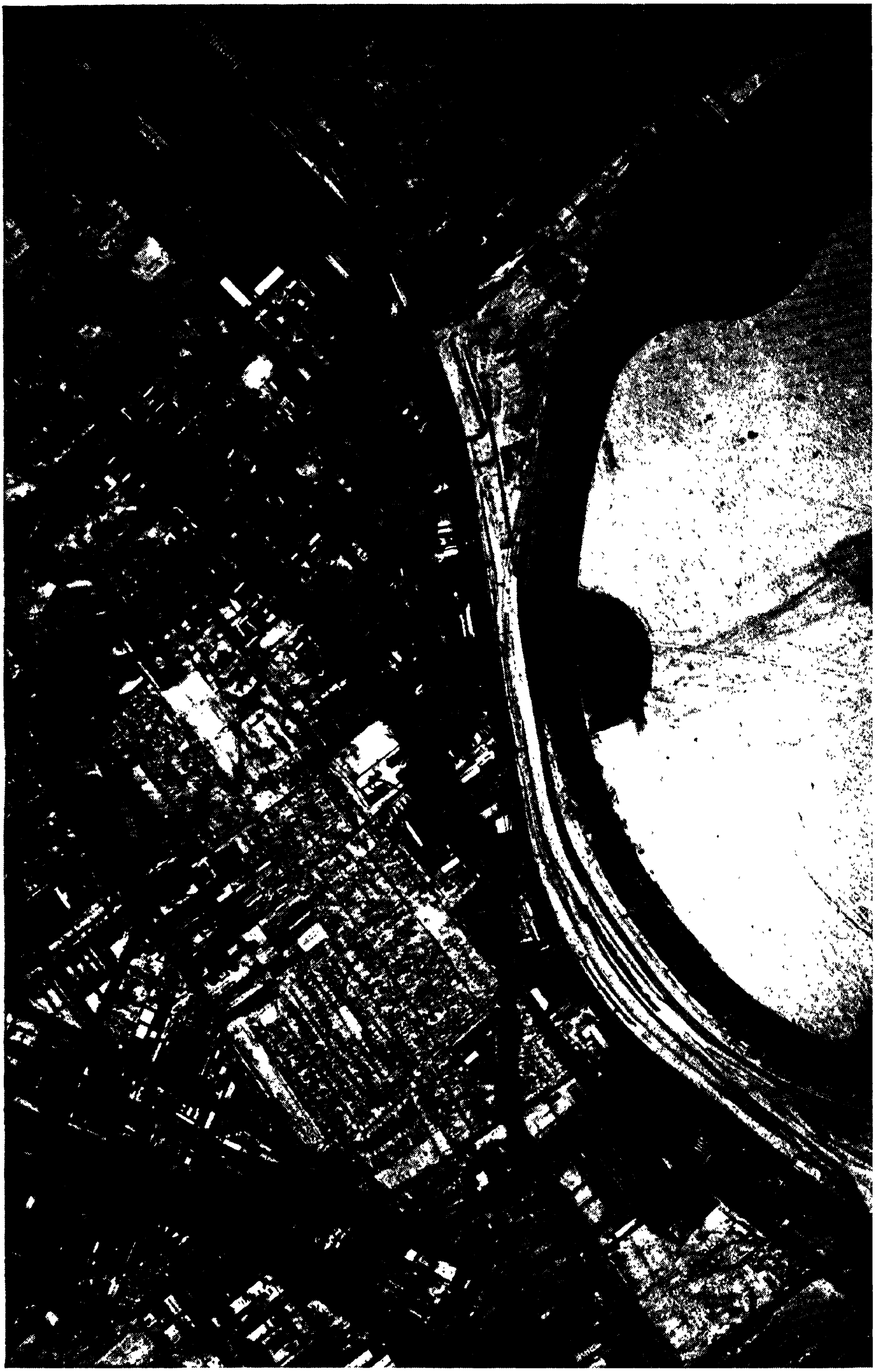


PLATE XXI
The Tempelhof district of Berlin after the raids of November, 1943.

accuracy and destructiveness, until in the end about 60 per cent of those areas had been destroyed or severely damaged. At the same time, the losses in raids guided by Oboe fell until in 1944 it was far below one per cent of the aircraft used. The losses of Oboe-fitted Mosquitoes were less than 0.25 per cent per sortie throughout the whole series.

Aircraft guided by Oboe and bombing from 30,000 feet at 250 miles drop on the average half of their bombs within 150 yards of the target. At 140 miles, from 6,000 feet, half the bombs drop within 45 yards of the target. The first Oboe stations were at Worth Matravers and West Prawle and were used for guiding attacks on the *Scharnhorst* and *Gneisenau* at Brest. They were followed by those at Cromer and Dover and others elsewhere on the South Coast. Twenty-four mobile stations were used on the Continent of Europe after the invasion. In an Oboe raid the main bomber force started first, flying at 20,000 feet. The Oboe pathfinders started later and were faster. They dropped marker flares every three minutes. The pathfinder was under Oboe control, while approaching the target, for about ten minutes.

War Science Leaves some Valuable Residues

The old methods of navigation by the sun and stars give the place of a ship at sea to an accuracy of about one mile. They give the place of an aircraft, when they can be used, to an accuracy of about 8 miles. Radar navigation under good conditions can give the place to an accuracy of a few yards. Radar may have led to terrible destruction, but it also provides, coupled with aerial photography, the means for survey and mapping of the earth with a new order of speed and accuracy, which will certainly lead to new knowledge of the earth and its possibilities.

SIGHT GIVES FREEDOM

A New Method of Seeing in the Dark is Conceived and Named

The radar aids to aerial navigation, the Masters and Slaves, the Cats and Mice, were limited in that they worked only within the range covered by the signals from the controlling stations. Further, the radar navigation aids depended on pulse signals that might be jammed by the enemy. If the enemy had discovered how to do that infallibly, the raids guided by these systems would have been entirely disorganized. Could there be any way of directly seeing the targets from the aircraft ? This would enable the navigator to see exactly what he had to do, and relieve him from being tied to

signals from ground stations, which restricted him to operations within a few hundred miles of them. Could not the navigator be given a target-finder which he would carry with him, making him entirely free from ground control, so that his range would be just as far as his aircraft could fly and return?

During a Staff meeting at the end of 1941, when the grave problems of the ineffectiveness of the current bombing methods were being urgently discussed, the need for a means of direct recognition of individual targets was repeated once more. What were these targets? Most of them were factories, built with steel frames. A member of the meeting reminded his colleagues of the difficulties they had had with the radar air interception equipments, used in the early night-fighting battles, from reflections of the radio waves from the ground. These interfered with the enemy aircraft being sought. Was it not to be expected that the steel-built factories would reflect radar beams, directed towards them by an attacking aircraft, with greater intensity than the surrounding countryside, and thus enable the pilot to pick them out exactly?

Such differentiation had been sought with 1½ metre waves, but without success. It was decided to pursue this suggestion, but with 10 centimetre waves. The first code name for the method was B.N. for Blind Navigation. But an eminent scientist who felt that it ought to have been used before is said to have commented that "the whole thing was stinking through not having been done years ago." Whereupon the method was named H_2S, the chemical formula for hydrogen sulphide, which has the smell of rotten eggs. This was, however, a little hard, for the system could not have been developed earlier, when centimetre waves were not available. Thus the most brilliant of the infants of radar was named, and launched on its life of growth and development.

Gestation of the New Method

The early workers on radiolocation had not overlooked the possibility of aerial navigation by reflection of radar waves from the ground. In the Summer of 1939, a flight was made from Martlesham to the West Coast of Wales, in which scientists using a 1½ metre airborne experimental set were able to give the pilot rough information on the route flown. This was done by using the 1½ metre set to measure the height at which the plane was flying. By comparing these measurements with a contour map of the district, it was possible to predict the course. The 1½ metre waves were too long, however, to promise any development in definition from an aircraft.

In the interval between 1939 and 1941 the ineffectiveness of bombing revived interest in the use of radar reflections ; the magnetron had been developed and great advances in the production of short waves had occurred. The 10 centimetre air interception sets had been produced, which presented the pilot with a rough television picture of the neighbouring enemy. This equipment whirled a radar beam which scanned the enemy aircraft, and led to a presentation of its position on a cathode ray tube before the pilot's eyes. Of the various methods possible with these very short waves giving very narrow beams we shall mention just two as illustrative of the principles, the helical scan and the spiral scan.

The idea of the helical scan is illustrated in Fig. 27 where we

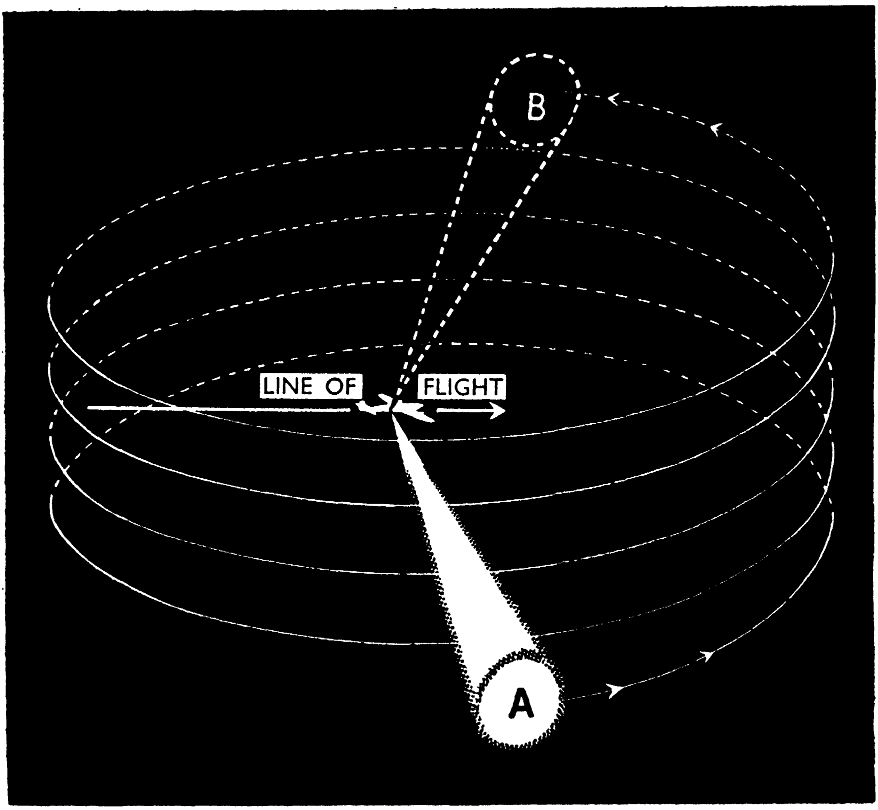


FIG. 27.—Illustrating the helical scan method. The nose of the aircraft contains a small concave mirror with a radiating dipole at its focus. This mirror rotates rapidly in such a way as to traverse with a beam of rays the helical path from A to B shown, for clarity, as sweeping the inside of a huge cylinder within which the aircraft is imagined to be. If successive whorls are arranged close enough together, the whole space within the cylinder is included in the scan

imagine an aircraft flying inside an enormous cylinder on a horizontal course from right to left. It has a short-wave air interception equipment in its nose with its tiny aerial mounted at the focus of a concave metal mirror rather more than 2 feet in diameter. The aerial and mirror act alternatively as transmitter and receiver. They first send out a pulse and then receive its echo.

Suppose that this mirror is rotated on a vertical axis, and at the same time waved up and down, as in Fig. 28. Then the beam will fall on the inside of the imaginary cylinder at A, say, in Fig. 27, and will travel around the inside on a helical curve until it reaches a maximum height at, say, B ; after which it will revolve down the inside on a similar helical curve, until it comes back to A. It can then travel again up to B, and back. By having the turns of the helix sufficiently close together, the whole of the inside of the cylinder can be kept covered, so that any enemy aircraft coming within this cylinder of space will be completely scanned. It will be covered by a virtually horizontal series of scanning lines.

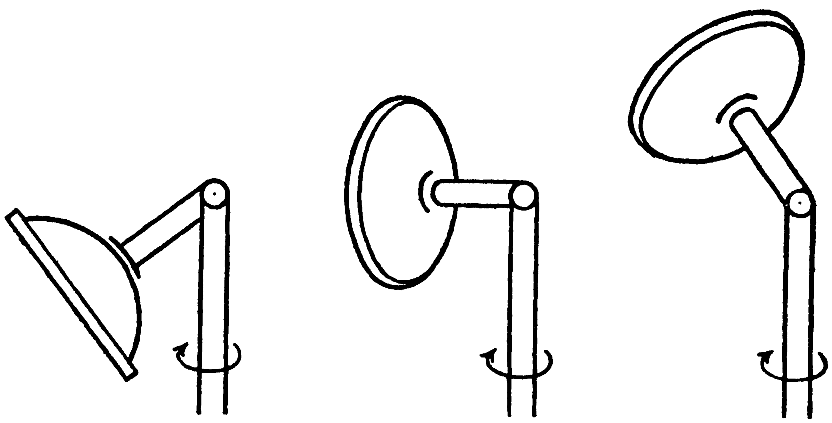


FIG. 28.—Showing diagrammatically the extreme positions of a rotating scanning mirror during its rotation,

The echoes from each sweep of the scanning beam can be represented on two cathode ray tubes, the first being swept vertically, and giving the range and bearing of the enemy, and a second swept horizontally, giving bearing and elevation.

Such was the essence of one of the air interception sets being experimented with in 1941. Another set with a different system of scanning was, however, preferred to it. In this, the scanning beam was revolved in an expanding and contracting spiral. Suppose we

have an enemy aircraft approached by one of our aircraft bearing a revolving beam of short radio waves. This beam is revolved in a spiral starting from the centre, so that each sweep of the spiral path touches its neighbour. In that way, the whole of a large area covering the view of the enemy aircraft can be scanned. The beam spirals out from the centre, until its angle with the line of flight of the aircraft is about 45°, and then spirals back again. The cycle out and back takes about one second, and is repeated over and over again. The echoes from the spiralling beam are built up into a corresponding picture on a cathode ray tube. This system was devised by Hodgkin, diverted to the radar war effort from the science of physiology.

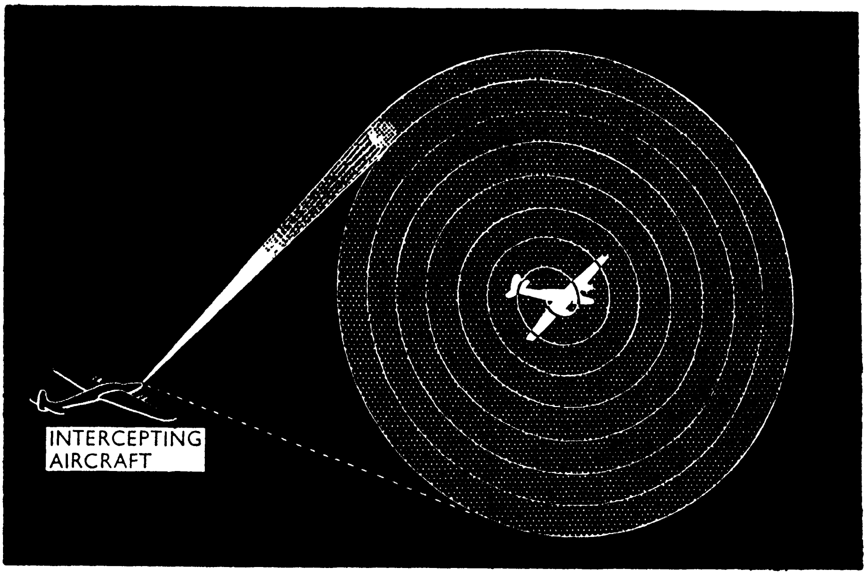


FIG. 29

If you could see air targets with these equipments, why not try to see ground targets with them ? Accordingly in the Autumn of 1941 Dee arranged that this experiment be tried. As there were some difficulties with the helical scanning equipments, it was easier to spare one of them at this time than one of the spiralling kind, so the first experiment was made with a helical scanning set working with 9 centimetre waves. The mirror was fixed in its depressed position (Fig. 30) instead of waving up and down, but otherwise it rotated in the usual way on its vertical axis. As the mirror was not moving in elevation, only the vertical-line range and bearing

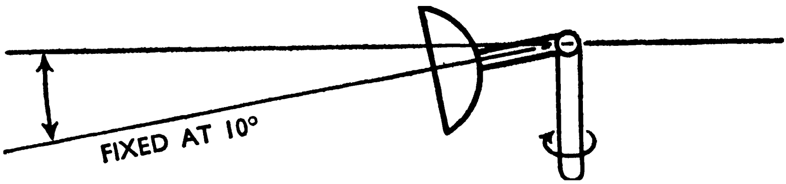


FIG. 30

picture was taken in the cathode ray tube record. The aircraft flew from Christchurch Aerodrome, Hampshire. After four minutes a camp near Stonehenge and the City of Salisbury were identified on the cathode ray tube.

Thus it was proved that in the cathode ray tube picture of the general reflections from the ground of the waves from a 9 centimetre airborne equipment, certain areas of ground could be distinguished from others. The picture of the mass of echoes from the ground was not just a shimmering confusion, it had definite features which corresponded to different objects on the ground.

Birth

Specific equipment for scanning the ground was now made, and fitted into a blister or dome on a heavy bomber, in the place of the under-turret. The blister was made of the synthetic plastic material perspex, which has the valuable property of being transparent to short radio waves, as well as visible light. The rotating scanning equipment is thus protected from the rush of the air. The bomber, Halifax V 9977, flew with the new equipment for the first time on March 27th, 1942, and radar (magic eye) target-finding was born to live under the name of H_2S.

Growth of H_2S

The development of serviceable equipment proved very difficult. At the end of May, the Telecommunications Research Establishment was suddenly removed from Christchurch to Malvern, owing to fear of reprisals for the British commando raid on the German radar station at Bruneval on the French coast. It was discovered, too, that the new very short waves travelled much farther over the sea than had hitherto been realized. With certain conditions of temperature and humidity in the air, the waves were bent so that they travelled almost parallel to the surface of the sea. One day the British researchers found very short waves being reflected back from the French coast. There were two important results ; firstly, that these waves could be used for picking up ships stealing along

the French coast, and thus act as sentinels over the Channel; and secondly, that the enemy might be able to pick up these waves on his listening sets, and learn something of the nature and direction of our radar developments. This, then, was a second reason for placing the radar research station out of the enemy's range.

But it upset the researches just started on H_2S. Then a disaster happened. The bomber Halifax V 9977 crashed in South Wales on June 7th, 1942, with its equipment and crew. All were killed, including the pilot, Pilot Officer J. D. Berrington, his crew, and five scientists working on the problem. These were Mr. A. D. Blumlein, an E.M.I. scientist of outstanding ability, Mr. G. S. Hensby, Pilot Officer C. E. Vincent, Mr. C. O. Browne and Mr. F. Blythen. Almost half the H_2S research team were wiped out.

The need for improved bombing remained as acute as ever. On July 3rd, the Prime Minister ordered that two squadrons equipped with H_2S should be ready by October. On July 5th Group-Captain Bennett, the future Pathfinder leader, who had just escaped from Norway, became interested.

Another major difficulty of policy remained. There was a fear that if an aircraft equipped with H_2S using a magnetron as its source of radiation were shot down over Germany, the enemy would capture the magnetron and thus have the scientific clue to the development of a devastating air-counter-attack on Britain. Experiments showed that the magnetron was almost indestructible. Demolition charges which tore a hole ten feet long in a bomber were not enough to prevent the remains of the exploded magnetron from being identified by an expert. The scientists were therefore instructed to use a klystron valve for H_2S. This was an older type, which the Germans already knew. Many months were spent in trying to develop a klystron valve for working the H_2S, but it would not give enough power. So again in July 1942 permission was given to use magnetrons. When the Germans first captured an H_2S equipment with magnetron in an aircraft that crashed at Rotterdam early in 1943, their scientific pride received a terrible shock. They found that at least five other technical features of the equipment were novel to them.

By the end of December 1942 more than fifty H_2S sets had been manufactured. Then, shortly before midnight on January 30th, 1943, the first H_2S bombers took off, to mark Hamburg. The weather was poor, and visual recognition of the port proved impossible. But when day dawned, and the crews had returned and had been interrogated, the first radar report from Headquarters, Bomber Command, concluded that " . . . H_2S is the most successful

blind navigation and bombing aid yet devised." Hamburg had been very easily identified, from the cathode ray tube picture of its shape ; and in two cases the river and docks were clearly seen.

Maturity

The mature forms of H_2S have an aerial which produces a beam of waves like a fan. It is very narrow in the horizontal plane and very broad in the vertical plane. The aerial rotates once in every

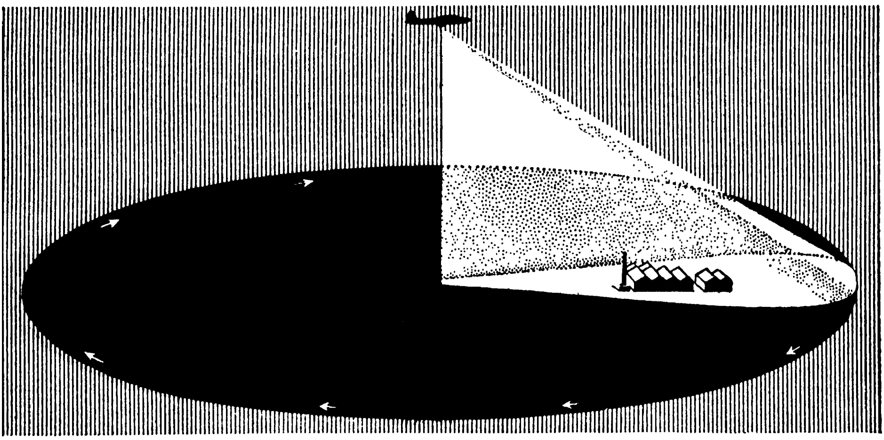


FIG. 31

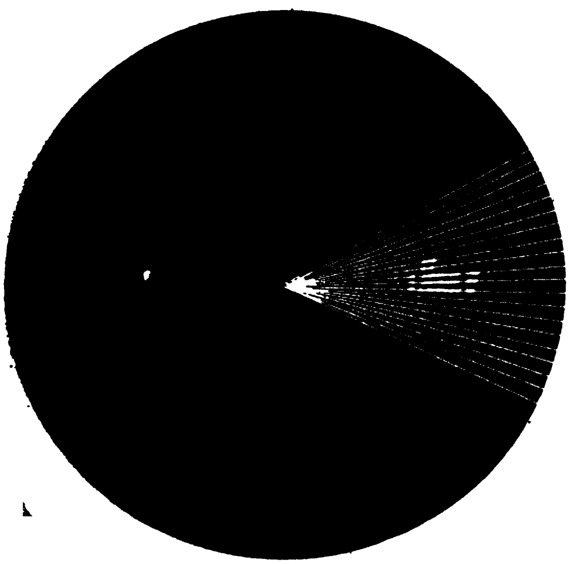


FIG. 32

second, so that the narrow band sweeps over the ground like the hand over the face of a clock. (Fig. 31.) The reflections from the features on the ground are recorded on a cathode ray tube, on a radius that revolves over the tube's face in unison with the revolutions of the beam over the ground. So the picture of a feature is left glowing on the tube (Fig. 32) as the beam goes round, covering it

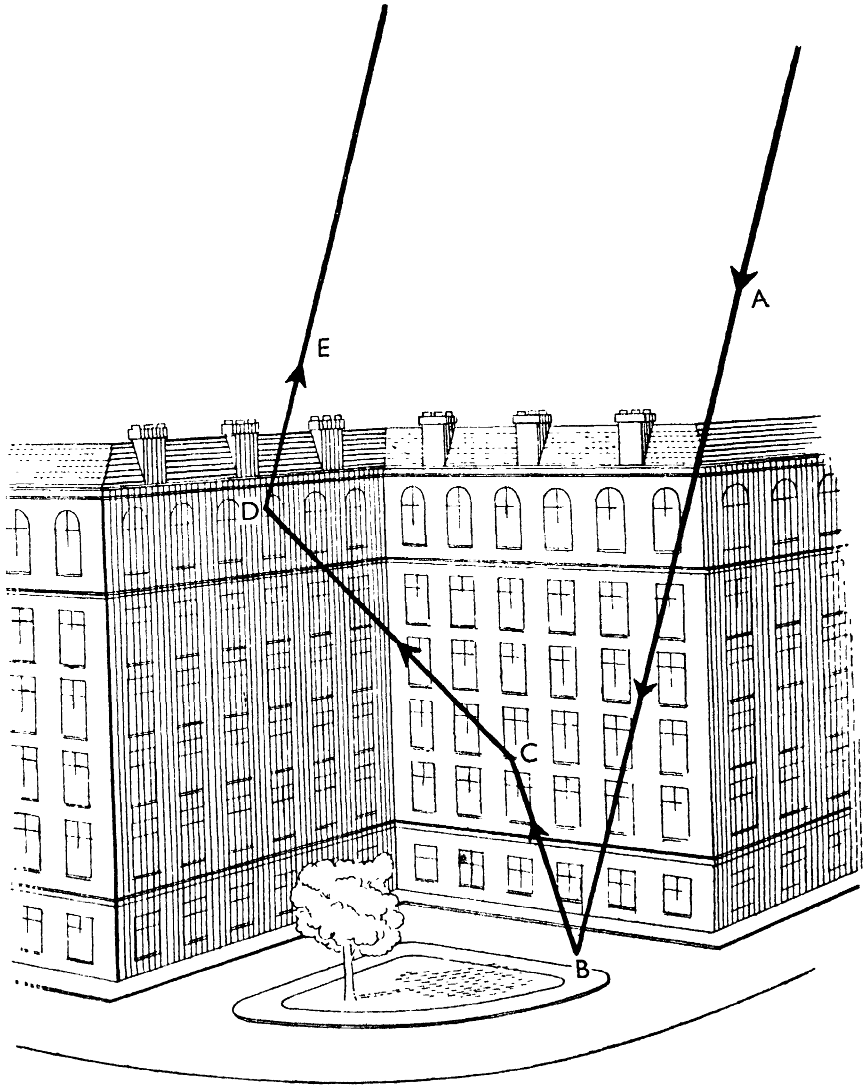


FIG. 33.—A ray reflected in succession from three mutually perpendicular surfaces, like the walls and floor at the corner of a room, comes back parallel to its original course. One such possible ray is shown as ABCDE.

over and over again, and producing echoes which give an illuminated patch on the fluorescent screen. Thus a crude map of the area below the machine is presented to the navigator of the aircraft.

The reflections that bring out towns so prominently come not only from steel structures but also largely from the many flat and vertical surfaces in the buildings. It is probably to some extent due to a characteristic of the reflection of rays from corners formed by three surfaces at right angles to each other. Suppose we have a block of buildings with two wings at right angles to each other, and a smooth asphalt yard between. Then we have three surfaces at right angles. If a beam of waves A (as in Fig. 33) strikes the asphalt at B, it will be reflected from the wall at C on to the adjacent wall, when it is reflected at D. It then returns in the direction from whence it came. This same principle of corner reflection has been known for many years in optics and has found practical application in peace-time as well as in war. Motorists will remember the brilliant roadside advertisement signs which showed up so well in their headlights, only to fade away when out of their beams. These signs are often studded with glass " corner cubes " each one made as if a slanting slice were taken off the corner of a cube. Such a section held with its point away from the eye, reflects back to the eye, with great efficiency, light starting from near the observer. In war-time these corner cubes were used particularly for marking sides of roads, which could be traversed at night using only extremely faint illumination. In some cases where particular precautions had to be observed, infra-red radiation was used for picking out the way.

Thus the reflections from the many surfaces and corners, as well as the steel structures in the buildings of a city or large factory, produce reflections much more intense than the diffused reflections from the countryside, and are in strong contrast to the very feeble reflections received from the sea and lakes and rivers. The navigator can identify coastlines, lakes, islands and estuaries, and parts of them, particularly well. He can do this in darkness and the densest cloud. Further, the rate of movement of the aircraft over the ground below can be easily measured, so that the wind-speed over the target can be calculated. Besides this, the bomb-aimer can be provided with an accurate measure of height above the ground. H_2S virtually sights the bombing besides finding the target.

ACHIEVEMENT

Destruction in Germany

In three great raids, on July 24th, 27th and 29th, 1943, led by Pathfinders using H_2S, Hamburg was laid in ruins. On December 3rd, 1943, Leipzig was found through thick fog and bombed. Eleven hours after the raid the smoke billowed up, as shown on Plate XIX. What it looked like when the smoke had cleared away is seen on Plate XX. In November, 1943, the bombers with an improved H_2S at last began to recognize details of Berlin. A series of successful heavy raids followed. The weather was so bad that from the beginning of November, 1943, until the second half of January, 1944, no photographs of the city could be obtained. But in the latter part of January and in February many photographs were obtained. One of them is reproduced in Plate XXI and shows the Tempelhof district with its large aerodrome. Between October 1943 and March 1944, 93 per cent of our strategic bombing effort depended on navigation and bombing with the aid of H_2S.

Sinking the U-boats

In the meantime, even more staggering results were obtained at sea. The first airborne sets for attacking enemy shipping and U-boats were similar to the 1½ metre air interception fighter equipment. The first sinking of a U-boat with their use occurred on February 10th, 1941. Later, they were carried by flying boats such as the Sunderland and Catalina, and, among other achievements, found the *Bismarck*. The capture of the French ports in the Bay of Biscay in 1940 had, however, made the enemy's U-boat tactics for attacks in the Atlantic very much easier, so that the sinkings of Allied ships gravely increased. The U-boats evaded air attack by submerging during the day, and surfacing only at night, when they could scarcely be seen under the best conditions.

In 1942 the situation was temporarily improved by the introduction of the " Leigh Light." This was a very brilliant searchlight with a flat but broad beam carried under the fuselage of a bomber, which could be switched on suddenly after the presence of a U-boat on the surface had been revealed by a 1½ metre airborne radiolocation set. In this way, surfaced U-boats were lit up brightly, and could then be bombed visually. The Leigh Light was introduced in June 1942. By August, the U-boats were afraid to surface at night, and came up during the day, providing possible visible targets. The enemy, however, found an effective reply. He listened to the radio waves from the airborne locators and, as soon

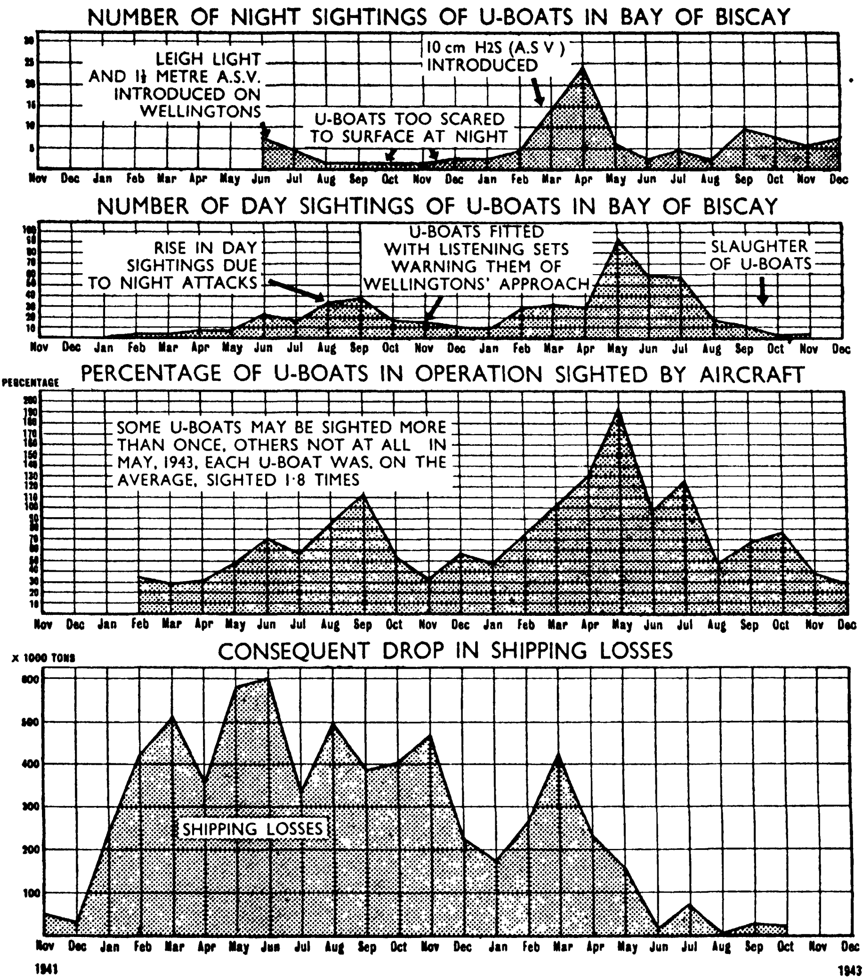


FIG. 34.—Graphs indicate how radar (A.S.V.) combined with a special searchlight (Leigh Light) affected submarine operations. *Graph I* indicates night "sightings," not necessarily "kills." *Graph II* indicates how U-boats came up during the day for battery charging. Kills were not heavy because the aircraft concentration in the Bay was insufficient. The drop in day sightings in the winter of 1943 was due to U-boats being fitted with aircraft warning receivers. Note the effect of British use of 10 centimetre A.S.V. which was hard for the enemy to "hear." *Graph III* shows percentage of U-boats known to be operating in the Bay. *Graph IV* shows the enormous drop in shipping losses as the U-boats were slaughtered in the summer of 1943.

as he found them, dived. During the winter of 1942 and the early months of 1943, very few U-boats were sighted at night or during the day ; and in January and February the sinkings by U-boats rose menacingly.

We evidently needed a U-boat-locating equipment whose radio waves would be much more difficult to pick up. The H_2S apparatus offered this possibility, so, in the autumn of 1942, it was suggested that some should be tried by Coastal Command's aircraft patrolling the Bay of Biscay. After many difficulties had been overcome, the first two Coastal Command bombers carrying H_2S left Chivenor aerodrome on March 1st, 1943, on patrol. Within a few nights, several U-boats were located on the surface, apparently quite unaware of their discovery, and attacked. Thirteen sightings of U-boats were secured in March and twenty-four in April.

The U-boats were slaughtered, and their sinkings of Allied shipping fell from 700,000 tons in March to less than 100,000 tons in August, never to recover. Doenitz in a speech at Weimar during the decline of the U-boat war said, " . . . the enemy has deprived the U-boat of its essential feature—namely the element of surprise—by means of radar. With these methods . . . he has conquered the U-boat menace. The scientists who have created radar have been called the saviours of their country. It was not superior strategy or tactics which gave him success in the U-boat war, but superiority in scientific research."

Thus it is not surprising that some important judges have seen in the change in the U-boat struggle, brought about primarily by the use of not more than 50 sets of H_2S radar equipment, the most significant single event which happened in the whole war of 1939-45. In the development of H_2S and this sea war application, much is owed to Dee, Lovell and their team at the Telecommunications Research Establishment.

THE REVOLUTION AT SEA

The Commander-in-Chief of the British Home Fleet declared that radar brought the greatest revolution in naval tactics since the change from sail to steam. It can detect the present of enemy ships far beyond the horizon, even through darkness and fog ; it raises naval gunnery to a new order of accuracy. The principles of detection and range-finding, upon which these two facilities depend, are the same as those which have already been explained with respect to aircraft.

Equipments suitable to naval conditions were designed by the Admiralty Signal Establishment (which grew out of H.M. Signal School), which contributed so much, especially in the development of radio valves, surface warning sets, fighter direction, navigation, gunnery, etc. It grew into an immense organization of 4,700 persons, under Captain B. R. Willett, R.N. He was succeeded at the end of 1943 by Captain P. W. B. Brooking, R.N., who organized the provision of radio and radar systems needed for the invasion of Europe. To mention a few names : Mr. G. Shearing developed silica valves for transmitters ; Landale developed at extraordinary speed the No. 271 very short-wave sets for use against U-boats ; Mr. J. F. Coales was personally responsible for the development of radar gunnery equipment now fitted in the Fleet.

Optical rangefinders suffer from certain fundamental defects, the most serious of which is that the error increases in proportion to the square of the range. Radar rangefinders, on the other hand, depend on the measurement of a difference in the time taken by radio waves to cover different tracks ; hence in general the error is constant and independent of the range of the target. It is of the same kind as that to which the timekeeper at a boys' sports meeting is subject. The timekeeper sees the boys start, and he presses the knob of his stopwatch. When the winner breaks the tape, he presses his stopwatch knob again. The error is about the same, whether the race is the 100 yards, 220 yards, or quarter-mile.

At the end of 1939, A.S.E. began to design a rangefinder using 50 centimetre waves. After much experimental work, an experimental set was fitted in a ship. Remarkably good results were obtained, due in part to the phenomenon of anomalous propagation, which was imperfectly understood at the time. The range of a convoy at 30,000 yards was successfully measured.

In May 1940, four months before the design was completed, an order was placed for components for 200 sets, and by the end of the year ships were being fitted with the set. Type 284 of these 50 centimetre rangefinders was fitted in H.M.S. *Suffolk*, and enabled her to pick up and shadow the *Bismarck* through the Denmark straits in 1941. This feat confirmed the sets' operational reputation. Their great day came when Type 284 materially assisted in the destruction of the *Scharnhorst*.

Radar ultimately gave the naval commander a complete moving picture of the battle situation which might be beyond the horizon, and in darkness or fog. It gave a picture of the whole of the convoy, so that the place of every ship and every escort could be seen at a glance, which was of enormous help during attack or in bad weather at night. It enabled the Gunnery Control Officer to

give all guns a range accurate to within a few yards, and to follow the slightest movement of the enemy. Small objects such as periscopes and conning towers, buoys, floating boxes, drifting dinghies with seamen and airmen survivors, pieces of wreckage, rocks, could be picked up at distances of several miles. Land could be recognized as a contour, and openings to harbours found. These navigational equipments were essential for the invasions of North Africa, Sicily, Italy and France. They reduced the effects of the weather and all elements of chance. Men were put ashore at the right place at the right time.

Radar gun-laying gave ranges accurate to within a few yards. The actual splashes of shot can be plotted by radar, and the system of gunnery " spotting " is superseded. Fire could be opened at greater ranges, and against unseen targets. A brilliant example of the greatest strategical importance was seen in the Battle of Matapan, which had a decisive influence on the war in the Mediterranean. It prevented the Italian Fleet from interfering with the withdrawals from Greece and Crete, relieved the Malta convoy situation, and turned the scale at the moment of our greatest peril. In this action, 7 metre radar sets warned our ships and brought them into instant fighting readiness long before the enemy knew of their

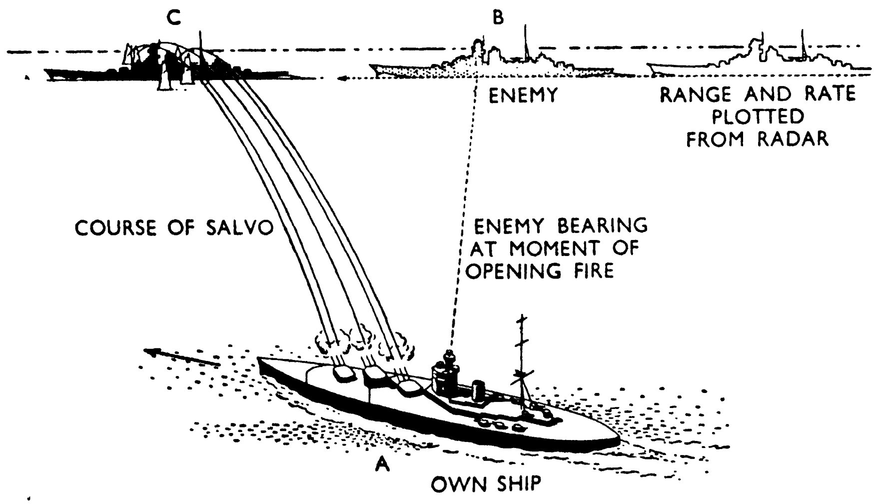


FIG. 35.—This figure shows that observations of the position (B) of an enemy, combined with a knowledge of his rate-of-change of position, enable his future position to be forecast, so that the guns will be fired in the right direction and set for the correct range so that the shells and the enemy will arrive together at C.

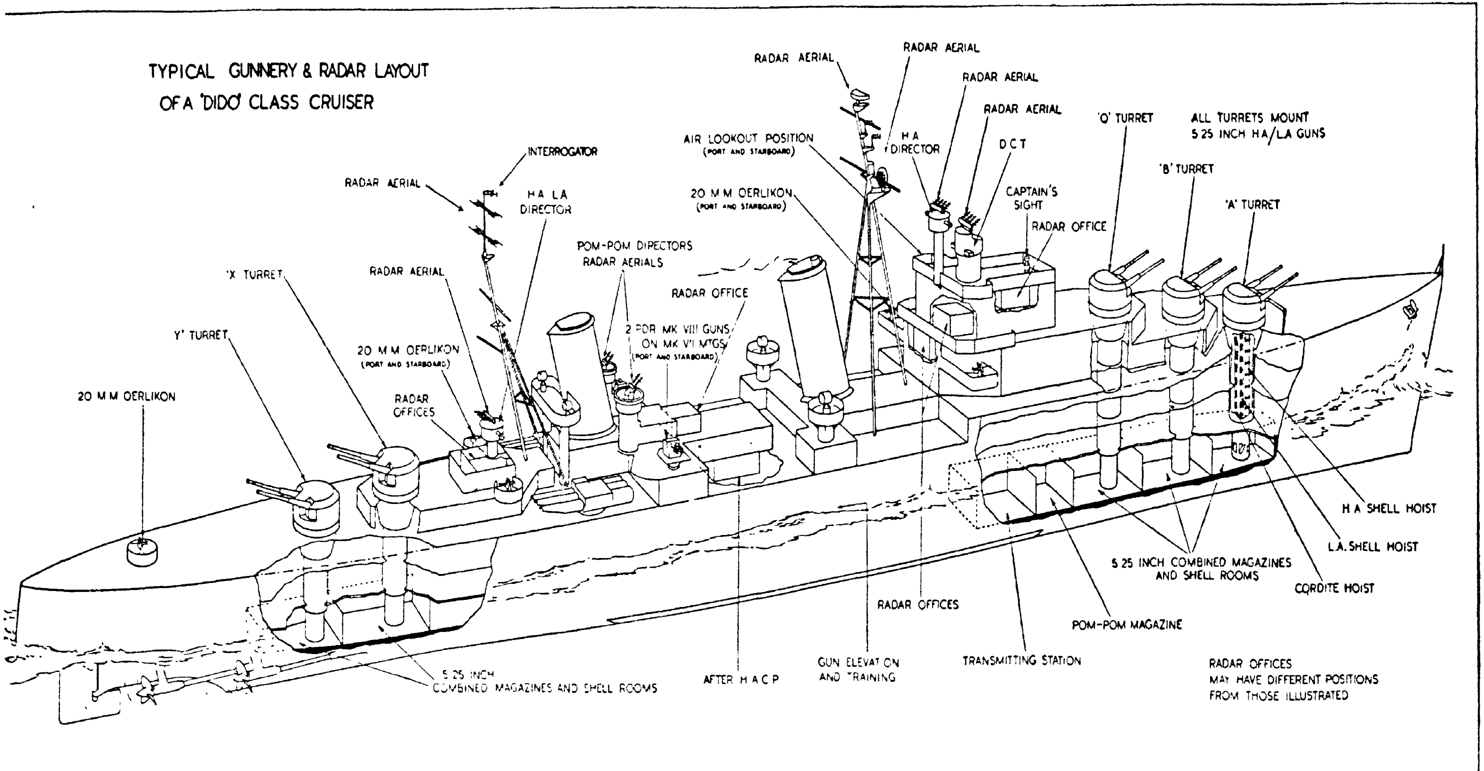

TYPICAL GUNNERY & RADAR LAYOUT
OF A 'DIDO' CLASS CRUISER
RADAR AERIAL
RADAR AERIAL
RADAR AERIAL
RADAR AERIAL
AIR LOOKOUT POSITION
(PORT AND STARBOARD)
H A
DIRECTOR
D C T
'O' TURRET
ALL TURRETS MOUNT
5 25 INCH H A/LA GUNS
'B' TURRET
CAPTAIN'S
SIGHT
RADAR OFFICE
'A' TURRET
INTERROGATOR
RADAR AERIAL
H A L A
DIRECTOR
20 M M OERLIKON
(PORT AND STARBOARD)
POM-POM DIRECTORS
RADAR AERIALS
'X' TURRET
RADAR AERIAL
RADAR OFFICE
2 PDR MK VIII GUNS
ON MK VI MTGS
(PORT AND STARBOARD)
Y' TURRET
20 M M OERLIKON
(PORT AND STARBOARD)
RADAR
OFFICES
20 M M OERLIKON
H A SHELL HOIST
L.A. SHELL HOIST
5 25 INCH COMBINED MAGAZINES
AND SHELL ROOMS
CORDITE HOIST
RADAR OFFICES
POM-POM MAGAZINE
5 25 INCH
COMBINED MAGAZINES AND SHELL ROOMS
AFTER H A C P
GUN ELEVATION
AND TRAINING
TRANSMITTING STATION
RADAR OFFICES
MAY HAVE DIFFERENT POSITIONS
FROM THOSE ILLUSTRATED

FIG. 36

PLATE XXII

The Leigh Light. This brilliant searchlight is carried by Coastal Command aircraft hunting for U-boats at night. The searchlight is shown attached to a Liberator aircraft, and being used to illuminate another aircraft during a test.

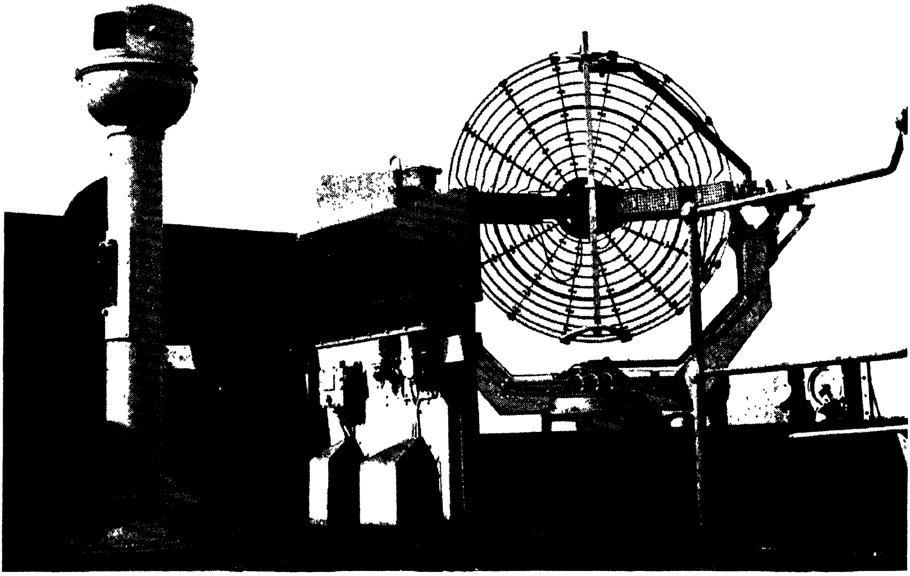


PLATE XXIII

The aerial of a centimetre-wave radar.

The bowl-like structure focusses the radar waves on the target acting like a searchlight mirror. It is usually in continuous rotation, in order to detect an enemy approaching in any direction. It can be tilted for observing aircraft and estimating their height. It is made like a grid in order to reduce wind-pressure and blast-pressure. Electric heaters are fitted to remove the frost and snow under arctic conditions. The rectangular " wave-guides " or tubes down which the waves are guided to the mirror focus are clearly seen.

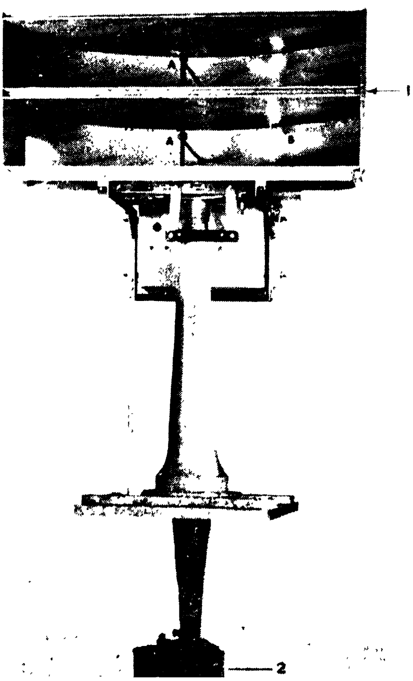


PLATE XXIV

The aerial system used with the early ten-centimetre (microwave) radars. The lower reflector focusses the radio waves emitted by the dipole (a rod about two inches long) into a narrow beam directed (by tuning the handwheel) towards the enemy. The upper reflector picks up the echo and focusses it on the upper dipole whence it is communicated to the receiver. This was the first ten-centimetre set in operational use, and was the first set capable of detecting submarines. To give protection from the weather and from curious eyes, the aerial was enclosed in a " lantern " with plastic windows.

PLATE XXV

The lower picture gives an idea of the land-marks which would be seen on the screen of the Plan Position Indicator by the navigator of a ship going up the Schelde to Antwerp. The picture is composite; the navigator would only see at one time the part covered by a sixpence. By means of this radar, ships were navigated up and down the river under conditions of almost zero visibility.

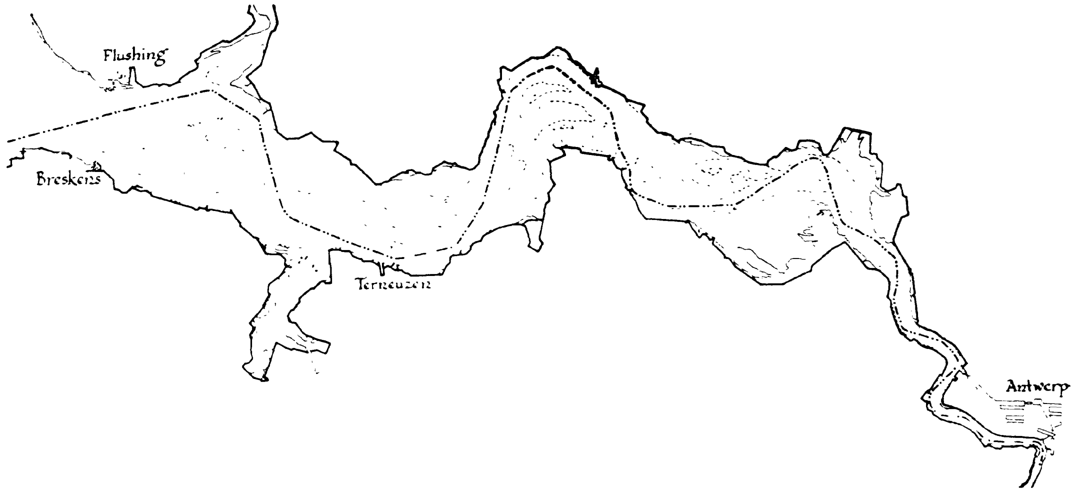


PLATE XXVI

An A.T.S. detachment at action stations on an Anti-Aircraft radar predictor.

PLATE XXVII

The cathode ray tube display on radar gun-laying equipment for the Dover Coastal Artillery. With its aid, ships near the French coast could be sunk in darkness or fog, when invisible from the English coast. Under special meteorological conditions much greater ranges than those set by the earth's curvature could be obtained (*see* Fig. 37), particularly with centimetre waves of short length.

presence. When the Italian ships were searchlight-illuminated a few seconds before H.M.S. *Warspite* fired her first radar-directed broadside, their guns were still trained fore and aft. Five of the six 15-inch shells in that first broadside secured hits. Three cruisers and two destroyers were sunk.

In the *Scharnhorst* action, the enemy was first detected with 10 centimetre equipment, far beyond gun range, by the cruiser *Belfast*, which presently opened fire, and caused the *Scharnhorst* to abandon an attack on a convoy for North Russia. The enemy was then shadowed by our destroyer force entirely through radar until the *Duke of York* was able to close with her and open fire at 12,000 yards range, 50 centimetre gunnery sets taking over the control. It seemed that the *Scharnhorst* was unaware of the *Duke of York's* presence until the first salvo. Most of those salvoes were fired " blind," and the deciding one was fired entirely on radar information. Thus a valuable convoy was saved in the difficult northern twilight, and a very powerful enemy ship sunk, most of the action having been " blind " and conducted by radar. In the actions with the *Scharnhorst* and the *Bismarck* the weather was unfavourable to visual detection, and it is very doubtful whether these ships would have been sunk without radar.

The pursuit of blockade runners and E-boats has been equally facilitated by radar.

The radar method of identification of friend or foe has been invaluable to the Navy, allowing gun crews to be at action stations before being attacked by cloud-dodging aircraft invisible until they fired their torpedoes or dropped their bombs.

The development of anti-submarine radar was of outstanding importance. It converted anti-submarine warfare from the defensive to the offensive. Hitherto, the submarine had, in the main, been counter-attacked only when it attacked. Henceforth, it was persistently hunted by radar from the moment it left port, and was gradually forced on the defensive and finally defeated.

The different conditions of fighting in the air, at sea, and on the land set different problems to the designers of radar weapons for use in these respective environments. Airborne radar sets must be light and compact in order to fit into an aircraft. Army radar for transport in the battlefield must not be too heavy : but as the direction of attacks on land is generally better known than at sea or in the air, all-round seeing is not so important. As the ship or the aircraft is more liable to be attacked from any bearing, rotating aerials are desirable. The ship has the advantage of being able to carry heavy weights with ease ; hence weight in a naval radar set is not such a serious drawback. Consequently, it is not surprising

to find that naval pressure led to the early construction of very powerful heavy sets. The gain in radar range with increase of power is very small, but at extreme ranges a slight advantage may be strategically very valuable, or decisive, just as an extra half-inch in reach may give a boxer a decisive advantage. Extra high power also leads to ease and certainty of operation. At sea, small aerials are desirable, owing to weather. This in turn raises the demand for high power. The seaborne set must withstand blast from the guns, vibration, corrosion, and, most important of all, underwater shocks. The explosion of a bomb or mine in the water near to a ship gives a shock which is very destructive to unsuitably designed radar equipment. For these reasons, the technical development of radar equipment rapidly diverges according to whether it is to be used in the air, at sea or on the land.

NEW ACCURACY ON LAND

Defence Against Air Attack

The retreat of the British Army from the Continent of Europe in 1940 brought the prospect of immediate attack and invasion of this island. Hence the new urgency for the application of science in land warfare was first concentrated in the sphere of defence, especially against attack from the air and sea. The Army, which was in charge of the Anti-Aircraft defences, looked to its Air Defence Experimental Establishment, which had been created out of the Army group formerly working on radiolocation at Bawdsey, for assistance in the radar field. This grew into the Ministry of Supply's Air Defence Research and Development Establishment under the distinguished physicist Cockcroft, and latterly the Radar Research and Development Establishment, under Mr. C. W. Oatley and later Mr. O. G. Sutton.

It was fortunate that General Sir Frederick Pile, one of the most devoted employers of scientists in the war, was in charge of Anti-Aircraft Command, and fostered the application of science to anti-aircraft gunnery. Radar had originally been created by an organization in which all three Services collaborated closely. The three main radio research establishments and their scientists have continued in exceptionally close collaboration, and air, sea and land problems have often been attacked not on the basis of Service interests and demarcation, but by the institution which happened at the moment to be able to do the job best.

The first radar equipment for aiming anti-aircraft guns was devised by Mr. P. E. Pollard in 1937. It was the basis of the first radar gun-laying equipment, G.L.1, brought into anti-aircraft

service in 1939. It gave range up to 10 miles, with an accuracy of about 25 yards, but no angle of elevation, and was the only equipment of its kind available in the night attacks of 1940-41.

Mr. L. H. Bedford, of A. C. Cossor, Ltd., devised an additional elevation finder, based on the reflection of the radar pulses from the ground. These were disturbed by uneven ground, so a level artificial ground made of wire-netting was provided to give uniform reflections. As explained later in the section on Operational Research hundreds of biologists and schoolmasters were recruited and trained to handle these sets—the A.T.S. and W.A.A.F. also were trained in their use.

In March, 1940, the first gun-laying set working on 50 centimetre waves was produced, and gave the ranges of aircraft at five miles. In June this set picked up echoes from enemy ships on the Cherbourg coast. It was not the first continuous observation of the Anomalous Propagation of short waves, that gives them a greater range than is to be expected, since similar effects had previously been noticed and exploited by naval users of radar. One of these sets was modified to work on the split beam principle and sent to aid the gunners at Dover.

In August, 1940, Anti-Aircraft Command had, on the average, to fire 20,000 rounds to bring down one unseen aircraft. By Spring, 1941, the number had been brought down to 4,000, and 100 enemy aircraft had been shot down. The very high priority for improvement in anti-aircraft gunnery led to direct collaboration between the three service radar research establishments in the construction of a gun-laying set using 9.1 centimetre waves.

The first model was produced in collaboration by T.R.E. and A.D.R.D.E. personnel, working first at their own establishments and later in the British Thomson Houston Company's factory at Rugby. Messrs. D. M. Robinson, L. W. Brown and R. Latham under Pollard's guidance led the development, and were much assisted by the interest shown in them by M.A.P. headquarters, through Dr. T. Walmsley, then Deputy Director of Communications Development. This was an early and successful example of the immediate introduction of a new model to the factories where it was destined to be made.

In April, 1941, two four-foot mirrors were attached to a searchlight turntable, and fitted with rotating dipole aerials, which gave split beams for measuring the angles of bearing and elevation. It could follow aircraft up to distances of 18,000 yards. Production of this style of equipment was in full flow in 1943.

As already mentioned, the 1940 Tizard Mission (which included Cockcroft) had taken to the American continent one of the early magnetrons and had thus stimulated early interest in short waves. The Canadians were naturally *au fait* with the British projects and themselves launched out into the design and manufacture of a 10 centimetre gun-laying set—a venture which turned out highly successful and most valuable.

The initiative for radar direction of searchlights came from three young scientists, Messrs. Chick, Eastwood and Oxford. They built a 1½ metre set in June, 1940, based on the equipment used in finding vessels at sea from aircraft. It was known as the Searchlight Control set, and was abbreviated to S.L.C., and then to *Elsie*. Searchlights were at first used in groups of three spaced at 10,000 yards, on the notion that the reinforcement of beams improved the chance of picking up the enemy aircraft. It was shown by calculation and experiment that if the searchlights were spaced at 3,500 yards, with one in three radar controlled, the chance of an aircraft being illuminated during the whole of its passage over would be raised to 70 per cent. This system was ultimately used. In October, 1942, research was begun on automatic following of aircraft by searchlights carrying their own 4-foot radar mirrors. By the end of 1943, aircraft were being successfully illuminated at night by automatic radar following. This system saved men, and the decline of exactness with fatigue. It enables much more rapid swinging and movement of the equipment than is possible with manual handling and for these reasons it is much more accurate.

In anti-aircraft gunnery, however, the main scientific triumph must go to the American scientists. They produced an admirable radar gun-layer which followed the target automatically by radar. With this and other American equipment, the flying bomb attacks of 1944 were defeated. Some 70 per cent of all the flying bombs were ultimately shot down, and for limited periods gunners shot down 100 per cent of the missiles coming within their range.

Coastal Defence

At the outbreak of war Cockcroft was asked to assist in strengthening the radar system of coastal defence. His colleagues adopted Butement's 1½ metre experimental radar equipment which had been designed primarily as a coastal defence detection set. Six of them were erected in the Shetland Islands for protection against approaching ships and aircraft. These sets detected fully-surfaced submarines up to 25 miles, and aircraft up to 70 miles, and it was amply confirmed that they were of the greatest use in detecting attacks by

low-flying aircraft on Scapa Flow. The stations, originally set up to detect submarines on the surface navigating the channels between the islands, became a major source of information about enemy aircraft to the fighter station at Wick from whence the intercepting aircraft came. These Coastal Defence units also were adapted for the Ground Controlled Interception system that became the key to the night defence of Britain.

At about this time (1940), the enemy began to use the first of his secret weapons, his magnetic mine. The east coast of Britain became littered with wrecks. The C.H.L. stations did not at once lead to much destruction of the enemy, but they did give much help to Naval minesweepers in finding mined channels, and to our own shipping.

" Centimetre wave " sets were soon adapted to coastal use. They had already by December, 1940, shown their promise in Skinner's hands ; he had picked up little ships in Swanage bay with 9.1 centimetre up to 7 miles with a mirror as small as 3 feet across, while the periscope and conning tower of a submarine was detectable at 4 miles. One set was installed on a gun-laying turntable, with a pair of 6-foot mirrors. It was taken to Dover in July, 1941. Ships were detected with it at 45 miles, and E-boats at 34,000 yards. Large shipping leaving Boulogne was detected and tracked through the Channel. It eliminated the need for standing Spitfire patrols which were previously necessary.

A special high-power set was then made for installation on the 700-foot hill at Ventnor in the Isle of Wight. It had a 400-kilowatt transmitter and a single 10-foot mirror. In March, 1942, the operators succeeded in detecting objects on the other side of the Channel with it. They found that in April and May these long ranges could be secured for 25 per cent of the time, while in June the percentage rose to 60 per cent.

This was a remarkable example of long range anomalous transmission, for it was far beyond the normal range of these very short waves. The fundamental reason for this anomalous transmission is interesting. It is due to the fact that the rate of travel of the wireless waves is very slightly changed by the constitution of the layers of air near the surface of the sea particularly in regard to their dampness. These dampness conditions are particularly marked in hot weather—when, indeed, for an associated reason, sea mirages are often observed. When the proper conditions are provided by Nature, the lower parts of the plume are bent round (see Fig. 37) as though they were, as indeed they are, trapped in a duct running

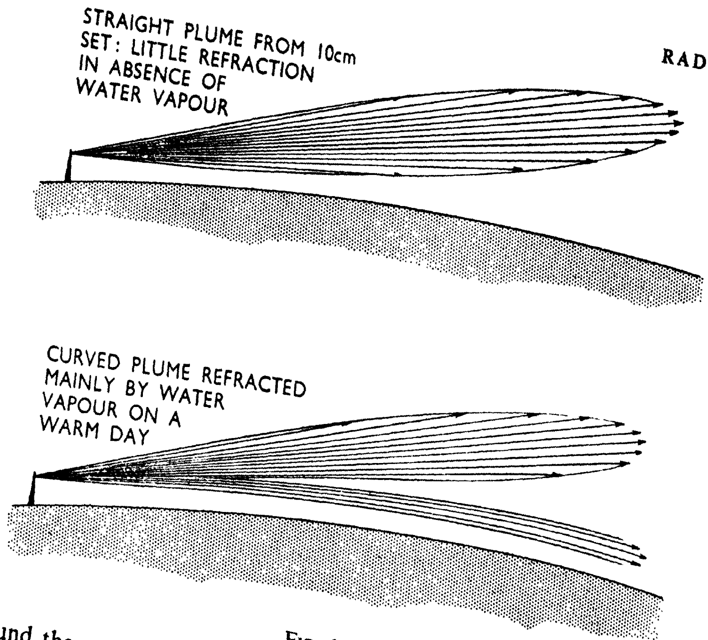


FIG. 37

round the curved surface of the sea. Such effects as this are very much less marked in overland transmission.

In August, 1942, at the time of the raid, Cockcroft was able to watch the shipping all the way to Dieppe, over 100 miles away. Motor-torpedo boats off the Cherbourg peninsula could be plotted and their interception be arranged.

Here was preparatory radar control of the Channel for the future invasion.

The 9.1 centimetre gun-laying set established at Dover recorded the splashes of 6-inch shells at ranges up to 20,000 yards. This became the basis of gunnery control by the radar observation of splashes. From June 1942, enemy shipping found passage through the Channel difficult.

It had been evident, from 1940, following a proposal of Butement, that fire control should be based on a cathode ray tube display of the position of targets and shell splashes. Late in 1941, such an equipment, working on 3 centimetre waves, was designed by Dr. A. E. Kempton of the Ministry of Supply's establishment (R.R.D.E.) it proved most successful, a later model being used in the sinking of a large proportion of enemy ships in convoy at long range by the Dover guns. This equipment was completed at Llandudno for trials in March, 1943. It had a 12-foot mirror, mounted on a gun-

layer revolving cabin, and became known as *Charlie*. It gave a cathode ray tube picture of a battle area 2,000 yards in range and three degrees in bearing, with an accuracy of about 25 yards in range. A set of this type was allocated to the Navy in 1944, and was installed at Dover in July of that year. Enemy shipping henceforth had extreme difficulty in passing through the Channel.

All the war-time uses of radar cannot possibly be enumerated in an illustrative account such as this, but there are a few which might be mentioned without close examination.

The detection of shell splashes at sea with 3 centimetre waves led to experiments for the Army on the detection of shell bursts on land. It was soon found that such sets could detect 5.5-inch shell bursts up to a range of 14,000 yards. Special sets were also made for following the trajectory of enemy mortar shells which were very troublesome projectiles.

Portable Radar sets for warning of the approach of aircraft were first used in the R.A.F. in 1941. In March, 1943, a hundred sets were prepared for North Africa, and were used in Montgomery's campaign from Alamein to Tunisia, and in the North African landings. Light sets mounted on trucks were important in the invasion of Normandy. They were put ashore almost with the first troops, and gave the maximum warning of enemy air attacks on the beach heads.

Special sets were made for the tactical control of anti-aircraft guns. These were used in the Normandy invasion with excellent results.

Centimetre waves were not only used for radar; the rapid advances of Field Marshal Montgomery on the Continent owed much to centimetre wave radio signal systems. The beams, 6.5 centimetres in this case, were focussed by mirrors facing each other and enabled ½ watt to do the work which would otherwise have required half a million watts. These sets, with almost optically straight beam paths, suited Montgomery particularly well, as he liked living in caravans on the tops of hills, which gave an uninterrupted field of short wave propagation from his headquarters to the various command points. The Ministry of Supply establishment was responsible for this outstanding effort, which was planned by Butement and carried out by Oxford, Anderson and McMillan.

The Radio Fuze

One of the most brilliant innovations of Army radar was the V-T or self-acting radio fuze. This was proposed by Butement. It

consists of a small radio transmitter and receiver fitted within a shell. When the shell is fired, the transmitter emits radio waves. These are reflected from the target. The time-interval between the emission of the waves and the return of their reflections is a measure of the distance between the shell and its target. By arranging that the shell explodes when the time-interval falls below a certain value, the shell is made to explode when it is within a certain distance of the target, and therefore virtually sure to inflict damage.

This very ingenious invention was based on an application of the Döppler principle, and on the use of very rugged radio valves which could be fired in a shell without being destroyed. Both of these original features were British inventions, the early successful rugged valves being made by the research team under Mr. D. I. Lawson of Pye, Ltd., while important contributions were made by the Research Laboratories of the General Electric Company, Ltd.

The later development and manufacture of this fuze were taken over by American scientists and engineers. Many very difficult problems had to be solved before it could be produced reliably in quantity. This was done just in time to meet the flying-bomb menace to London, and at the end of that attack, nearly 100 per cent of all the flying-bombs approaching London were being shot down by anti-aircraft guns using V-T fuzes invented in England, and developed and manufactured in the United States.

There are three stages in military scientific research : (1) the initial brainwave: checking it to see whether it is consonant with the laws of nature ; (2) the making of hand-made specimens, which are, in general, no use for the Services ; and (3) development for production. England had too few experts in the third of these categories, owing to absolute limitations of man-power, and also, no doubt, to an insufficient proportion of development engineers in her educated population. Owing to this, there was a tendency in England to turn first-class physicists into second-class engineers, in order to try to fill the gap. Our American allies were able to put 1,500 persons on to the development of this fuze : at no time were we able to put more than 50 persons on to the same task. The Americans performed the prodigy of making 150,000,000 of the special valves for these fuzes.

INGENIOUS AIDS

Besides the main radar equipments there are many special aids of great ingenuity. There is for example a variety of radar beacons, which " speak " only when they are spoken to, with the important difference that unlike the older radio beacons, they give range as

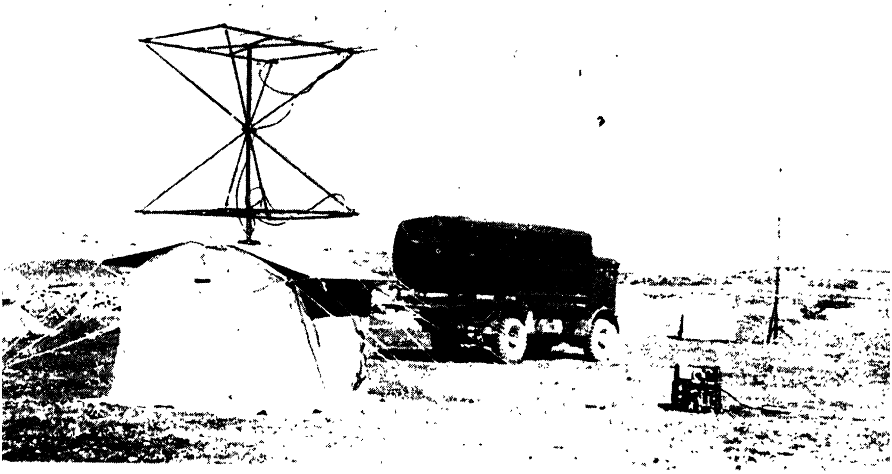


PLATE XXVIII

A Light Warning Station. The entire equipment and personnel can be transported in one three-ton vehicle, and can be erected within two hours of arriving at the site. It can be transported to otherwise inaccessible places by mule, or even by men, if necessary. The aerial system consists of two pairs of Yagi arrays, one mounted above the other. It gives rapid coverage to a new camp or aerodrome, up to a distance of about 50 miles, working on a wavelength of 1½ metres.

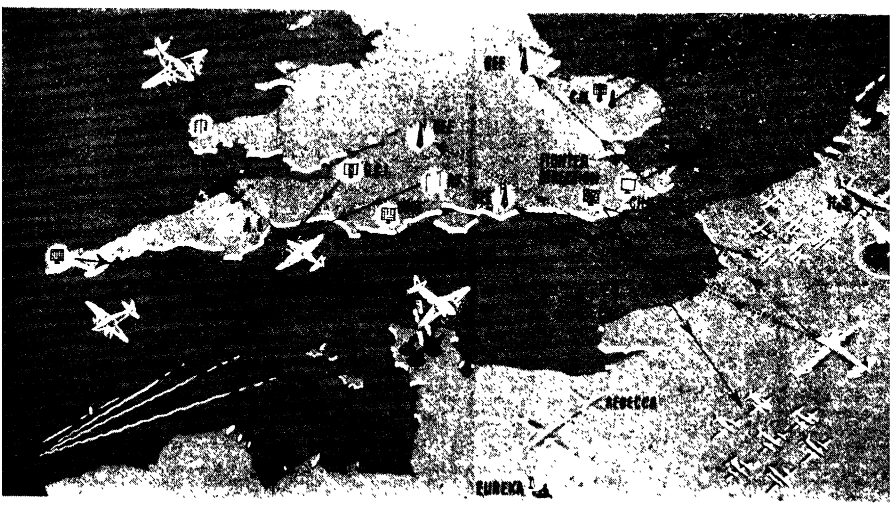


PLATE XXIX

The picture shows the main radar aids used in Southern England. The C.H. stations are to detect the attacking enemy. G.C.I. assists interception of a raider. Oboe guides our own bombers on to enemy targets. Gee is shown as assisting our bombers to return. C.H.L. detects low fliers. A.S.V. enables the bomber to attack ships. H_2S enables the bomber to find its target. Lucero is an aid which interrogates both homing beacons and other aircraft. Rebecca and Eureka are the interrogator and the beacons used by invading paratroops.

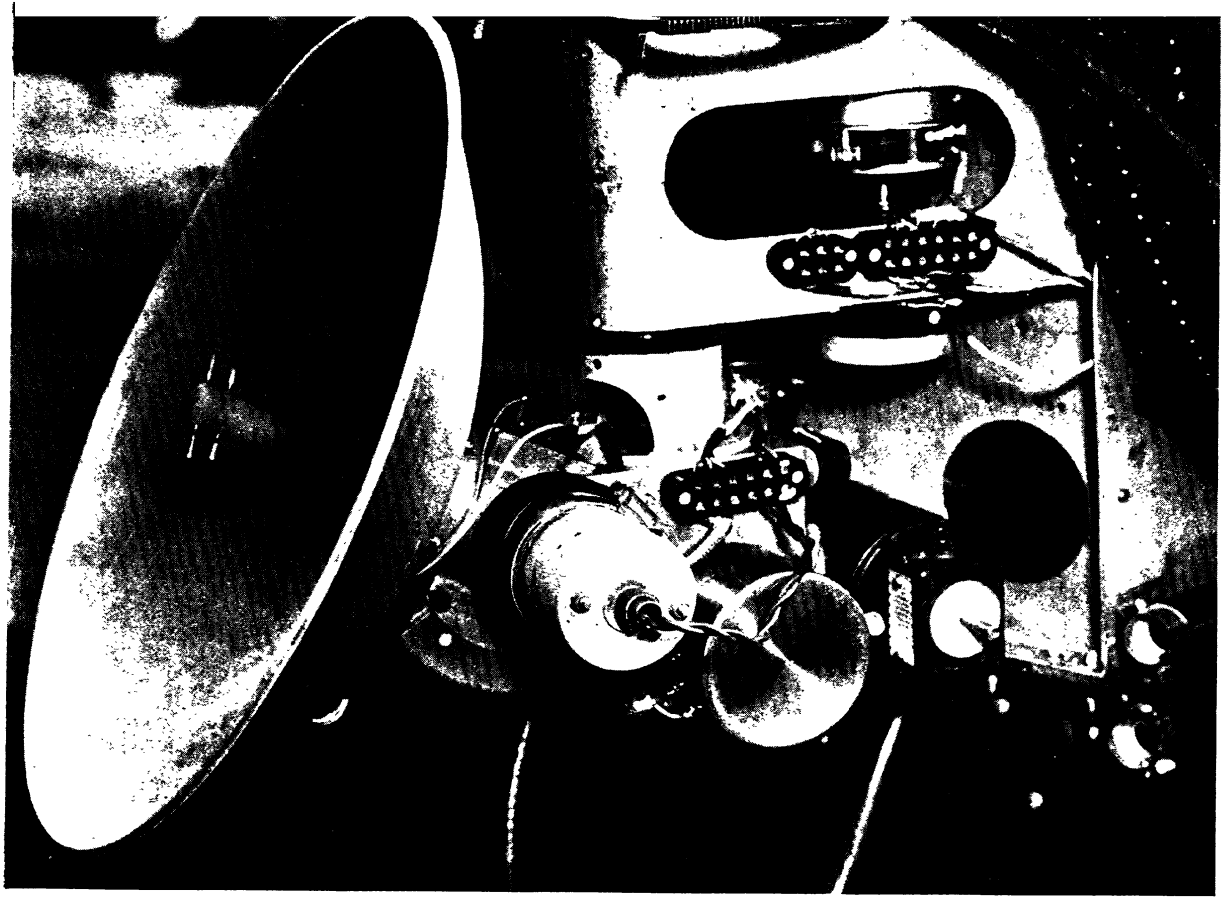


PLATE XXX

Protecting the air crews. Airborne gun-laying turret in the tail of a Lancaster bomber, showing the scanner with transmitting and receiving dipole aerials. The equipment gives the rear gunner information on the position of attacking fighters, and among other details, it gives a warning to the rest of the crew through the intercommunication system.

PLATE XXXI

A research laboratory at the Telecommunications Research Establishment. Research is being carried out on wave guides, some examples of which are displayed on the bench in the foreground.

PLATE XXXII Participators in a Sunday Soviet at the Telecommunications Research Establishment, Malvern.

Sitting : A/Cdr. W. C. Cooper, A/Cdr. C. S. Cadell. A/Cdr. W. P. G. Pretty, Sir Robert Renwick, Lord Cherwell, A. V. M. Sir Victor Tait, Mr. A. P. Rowe, Mr. D. W. Fry, A/Cdr. C. P. Brown, A.V.M. W. E. Theak, G/Cpt. E. C. Passmore, Dr. F. C. Williams, Mr. C. Holt Smith, A/Cdr. M. K. Porter, Dr. W. B. Lewis.

Standing : A.V.M. O. G. W. G. Lywood, A/Cdr. G. P. Chamberlain, G/Cpt. J. Shepherd-Smith, G/Cpt. G. N. Hancock, G/Cpt. C. A. Bell, Prof. D. M. Robinson, Mr. C. J. Carter, S/Ldr. W. H. Thompson, G/Cpt. C. C. Morton, Mr. J. C. Duckworth, Mr. E. H. Cook-Yarborough, Dr. R. A. Smith, Mr. A. B. Jones, Mr. J. Stewart, Dr. A. T. Starr, Dr. T. C. Keeley, Dr. A. H. Cooke, G/Cpt. J. A. Macdonald, Mr. R. J. Dippy, Dr. D. A. Jackson.

well as bearing. The principle is the same as that of an identification-of-friend-or-foe. The aircraft carries a transmitter called an interrogator, which transmits pulses on one frequency. The beacon contains an apparatus called a transponder, which picks up the pulses and re-emits them on a different wave-length. These are received on an apparatus called a responder, which includes a cathode ray tube, on the aircraft, and the navigator reads his range and bearing from their records. Such beacons work up to ranges of 80 miles. They may be used as homing devices, by which aircraft can find their way back to aerodromes and aircraft carriers, and by which troops on the ground can signify their position for co-operation with aircraft, in the dropping of airborne troops and supplies, etc. The interrogator is called *Rebecca*, and the homing and identification beacons *Eureka*. They were an important aid in the invasion operations on D-day, and the following days. Some homing beacons do not radiate in all directions, but send out a split beam. The axis or equisignal, as it is called, of this split beam may be laid more-or-less along an aerodrome, to assist aircraft to land. The equipment is known as *Babs*.

These many and other applications were supported by the invention and development of hundreds of electrical mechanisms : for example, servo systems, by which apparatus is made to operate electrically instead of by hand ; and the Velodyne which is an electromagnetic system that integrates the resultant of several motions, and can provide the answer to information fed to it by radar signals. The cathode ray tube receivers display the radar information received by them, in many different ways. There is a variety of systems for measuring the time intervals between reception of pulses and echoes and special spots, or strokes, that move over the face of the cathode ray tube with so much meaning that they almost talk. In all of this particular group of developments, and in that of the radio beacons, F. C. Williams made brilliant inventive contributions.

Another remarkable invention is that of the Skiatron. It is a modified cathode ray tube but provided with a special kind of screen made of fine crystalline potassium chloride. When the electrons strike these crystals a black patch develops which persists for a time which depends very much on the temperature at which the screen is held. It disappears more quickly at a higher temperature. The underlying physical principle is not yet quite clear ; it was at first thought to be due to the liberation of metallic potassium, but may be due to some not yet completely understood phenomenon caused by the trapping of some electrons within the crystals of the screen. Whatever the explanation, however, it is a most useful property

of a sylvine screen to behave in this way. It is quite easy to treat this screen with its black marks and traces as an epidiascope lantern slide, and to project a magnified image of it on a screen. This is a great advantage in a war room, for example, where a number of people can see the display of distant aircraft or shipping much more conveniently. Such a screen projection would, of course, not be possible with an ordinary cathode ray tube because the brilliance of the spot is not sufficient to show up on a large screen. This instrument was developed by Sutton and his team at Bristol from a pre-war commercial device.

It will be seen that radar has been a vast innovation, involving thousands of scientists and engineers, and tens of thousands of productive workers. The main Service radar research establishments alone had a total staff of more than 10,000, containing perhaps one third of all of the appropriate kind of physicists in the country. The avariciousness of radar for scientific talent caused it sometimes to be referred to as "that rapacious beast." During the war, about £50,000,000 worth of radar equipment was produced annually by British industry, and nearly half of the army of 250,000 workers producing all kinds of radio equipment were concentrated on the radar section of this production.

SUNDAY SOVIETS

Radar is far more than an aid even if it cannot properly be given the full dignity of a whole new branch of science like optics, for example, which deals with "visible" light, or like acoustics which deals with the properties of sound. The foundations of this very practical branch of applied science, which we call radar, were long ago well and truly laid, but it was only during the war that such complete practical mastery of the shorter range of centimetre wavelengths was so brilliantly and rapidly achieved. Their successful generation, projection and reception has in large measure been responsible for opening up all the fascinating possibilities and actualities useful in war—destined to be still more useful in peace.

Its immense scope and variety are apt to absorb the complete attention of the young men who have entered it straight from academic studies, and have no experience of research in any other branch of physics. This is reflected in the story of the two young radar workers, one of whom said to the other: "What is this physics of which we hear so much?" to which the other answered: "I believe it is part of radar." Here was complete and indeed, over-absorption in the new branch of science, but it revealed the

magnitude of the new subject, and the pride and enthusiasm, and the limitations, of its devotees.

The most significant of all the aspects of radar was not the size and variety of its application, and its direct assistance in crucial battles: it was in the method and spirit of its researches. These contained something new, which was more powerful than any particular scientific invention. When the development of radar began at Orfordness and Bawdsey in 1936, the subject was entirely new and, owing to the need for secrecy, was restricted to a very few persons. Thus work on radar was fresh and the relations between those engaged on it were exceptionally intimate. A small number of officers and officials from the Army, Navy and Air Force came to study the work and join in it, on behalf of their own services. As the subject was highly novel and technical, they necessarily came as learners, as well as prospective users. Owing to these reasons and the ability and imagination of the men concerned, the development of radar started with a new degree of variety and equality in collaboration. Hence one of the chief differences in the use of science in the war of 1939-1945 as compared with former wars was the extraordinary intimacy between deviser, user and producer.

With regard to radar, admirals, generals and air marshals came from the very first to see what was being done. They did not tell the scientists that they wanted this or that, but stated their problem and asked what science could do about it. The staff officers got into the habit of bringing rather diffuse problems to the scientists, and general discussions went on between admirals, air marshals, lieutenants, pilots, scientists, laboratory assistants, development engineers, and anyone who could help.

On many Sunday mornings Rowe held informal discussions in his office. These were attended by Watson-Watt, Royal Air Force officers joining in almost at random. There was a tendency to discuss specific subjects on specific Sundays, but there was no agenda. These meetings, as they developed at the Telecommunications Research Establishment, became the occasions for free and informal mental attack on the vital scientific problems of the war. In 1940 and onwards the pressure of day and night bombing and submarine attack furthered the formation of a new way of attacking military problems. At these Sunday meetings, operations of a whole command were discussed. Anyone, including the most junior civilian, who had anything useful to suggest was invited to come in. Some of the keenest and best minds in the world, already famous for their researches in other fields, together with the fresh minds of gifted

young scientists and engineers, looked at major problems of the air and anti-submarine commands, and submitted them to free, equalitarian and ruthless scientific discussion. The proposals of the scientists were submitted to equally searching criticism. The pilots said what could and could not be done in an aircraft, the men from the factory would tell the scientist who made too many suggestions for alterations, " You can't change that in the production line," and some continuity of production would be preserved. At the same time, the man from the factory could appreciate why changes had to be made.

Owing to their character of complete equality and outspokenness, these meetings were called " Sunday Soviets." This " soviet " group system was an excellent way of getting direct answers to problems depending on the inter-play between several sides or groups. It supplanted the old system of doing research in series and replaced it by research in parallel. In the old conception of military scientific research, the scientists were more often than not asked to investigate certain specific points, instead of having the problem put to them. But in this war it was often indubitably clear that the fighting man could not define his own problem, even to himself, and even less tell the scientist what it was or what some specific requirements in connection with it might be ; he could not do so because often the definition of his problem depended on scientific knowledge that he did not possess. At the Sunday Soviets, the fighting men often described vague situations, which were reduced to definite terms by all-round discussion. And once a problem is adequately stated, you are usually halfway to its solution. One of the great occasions of the war was, though actually this was not at a Soviet, when Air Marshal (now Sir John) Slessor, then Commanding Officer of Coastal Command, took off his coat and had a free-for-all on what could be done about a submarine. He then wrote a formal specification of what was wanted. This was conceived with direct experience of the scientific factors involved and was not an office conception based on vague operational reports.

In these discussions, scientists of very different types were able to make their own special contribution. Some, such as Dee and Lovell, excelled in brilliant conceptions and in pushing them through. Some of the most valuable scientific efforts came from men who made few scientific experiments themselves, but submitted problems to logical scientific examination, and told inventive geniuses what was wanted, nursed it out of them, and then persuaded the officials and the fighting men to appreciate and use it. Some, such as Dippy and Reeves, stuck to one major problem for years and pro-

duced one major result ; others, such as Williams, Hodgkin, Pollard and Butement, turned rapidly from one problem to another, and produced series of inventions. Major scientists, such as Cockcroft, Dee, Lewis, Oliphant and Skinner, helped to conceive military scientific problems from the most profound scientific point of view. The great contribution of these men was a demonstration of the fundamental importance of abstract research. Rutherford was often criticized for training " atom smashers," who did not appear to be of any practical use to the nation. How right *he* was ! His own nuclear physicists and their colleagues turned to radar, and in a few months helped to revolutionize it. Then they laid the foundation for the invention of the atomic bomb and the industrial use of atomic energy. We saw how rapid transference from atom smashing to war problems was, and could be. Another feature was the strong feeling of brotherhood among scientists. Each one of standing was in close touch with others in his own field, so that when he entered into military scientific research he brought many others with him, and benefit was drawn from all.

How did all this compare with the situation in Germany ? In 1940 the German General Staff believed they had won the war. They issued an order that no scientific research or development should be pursued which would not be of military use within four months. They drafted scientists into the armed forces to assist in the invasion of Britain. They did not realize until the end of 1942 that new scientific developments would be necessary if they were not to lose the war. A director-general of research in short-wave radio and radar was then appointed. But in the years from 1940 to 1942, British radar scientists had leapt too far ahead ever to be caught up. The Germans had nothing like our T.R.E. Sunday Soviets with their integral co-operation of scientists and operational leaders. The Luftwaffe and the German Army and Navy gave contracts to the big electrical firms to make equipment according to specifications. The firms competed for these very profitable orders, and produced beautifully engineered equipments. But the absence of collaboration between user and maker in fundamental research on their common problem often led to waste of effort and the production of unsuitable, though splendidly made, equipment.

For instance, the Luftwaffe told two of the great German electrical firms that they did not want radar, and asked for tenders for some slightly improved radio equipment. These firms worked for two years on the development, and then the apparatus of one firm was accepted. The two years' effort of 500 scientists and

engineers in the competing firm was wasted on trying to secure a small technical improvement instead of doing something more important. It seems that one German company offered to the Luftwaffe in 1938 a system of radar navigation resembling the British *Gee*, in which aircraft were to be guided among hyperbolic paths ; but it was rejected.

In secondary features, German equipment was often superlative. For instance, they would produce sets which were not noisy at the top of the very short-wave band. The German engineer was generally very good, but he was not able, or not allowed, to get to grips with the real operational problem. In contrast, British equipment was rougher, but fundamentally better ; because it was based on more advanced scientific ideas.

In the Summer of 1942, Hitler while at his headquarters at Kalinovka in South Russia sent for General Martini of the Luftwaffe to question him on the subject of short-wave radio. He told Martini that he did not believe in it, because he had set out on a flight in South Germany and had ended up in North Germany, owing to mistakes in short-wave navigation. He said he did not believe in the effectiveness of short-wave technique, and he could not believe that the Royal Air Force could bomb Krupps through complete cloud with its aid. He asked Martini to explain, and demanded more and more details, insisting on going through each of the calculations himself. Martini became more and more confused, and Goering, who was present, looked obviously troubled. In this atmosphere nothing like the Sunday Soviets was possible, where air marshals, scientists, laboratory assistants, pilots and everyone met on a completely equal footing for the collaborative discussion of the common problem, from every point of view. The German lack of this factor was one of the chief causes of their loss of the war, and our possession of it one of the chief reasons why our defences, our bombing and then our battle against the U-boats reached the pitch of success that made victory first possible and then certain.

In the field of radar, the Germans were not lacking in scientific and engineering resources. Indeed, their scientists as a class had more prestige than our own. But they were weak in collaboration. Each German scientist felt that he had to be individually brilliant, and there was a great deal of independent and isolated effort in research laboratories dispersed all over the country. These scientists were, however, never made really aware of the fundamental problems and needs, knowledge of which could only come through the meeting and collaboration of all interests.

Our own greatest achievements, such as the development of the magnetron, came through the breaking down of barriers between different fields of research and ideas. The pre-war literature of high-frequency electricity was pregnant with centimetre waves. The clear grasp of the need for them by the combined British military and scientific interests focussed powerful attention on the problem, and provided the conditions for its solution.

What conclusions are to be drawn from the British and the German stories of radar? That the British found a far better method of organization and collaboration of scientists, military users and industrialists. This enabled them to see further, and solve deeper problems, thus enabling them to provide our forces not only with more potent weapons, but with more profound ideas as to how they should be used. On the whole, our scientists more successfully subordinated themselves to team-work, while at the same time developing courage and determination in struggling for the correct scientific policy. We always had men of the highest scientific eminence, directly engaged in the laboratory and technical struggle, who insisted on explaining what the real scientific situation was to every eminent person, in science, in military affairs, in industry, and government, who ought to know. And, fortunately, the eminent in these other fields listened, sooner or later.

The real German scientific defeat, surprising as it may seem, was in the field of organization. They organized industrial production and the Army superbly ; but in the field of radar they failed to organize teamed collaboration between scientists, fighting men and industrialists. The reader will decide for himself how far that fundamental failure arose from the nature of Nazism and German social traditions, and how far our success arose from the practice of democracy.

II.

OPERATIONAL RESEARCH

The development of operational research was one of the chief scientific features of the war. Through it, science entered into warfare in a new degree. Hitherto, science had been chiefly regarded as a source of ideas for new weapons, and a method of improving old ones. It helped to make better explosives, faster aircraft, bigger guns and better medicines for treating the wounded. It provided the fighting man with things to fight with. This dependence of the fighting man on science, and indeed of science on the needs of war, is ancient and well-known. Archimedes made catapults for the Greeks of Syracuse to resist the Roman invaders. Medieval chemists made gunpowder for the first artillery. Leonardo da Vinci designed multi-barrelled guns, tanks, submarines and parachutes for military ends. So science helped the technique of warfare. And in return warfare helped science by the invention of the medical hospital, first produced by the Romans for treating their wounded soldiers ; and in setting gunnery problems in the aiming of cannon-balls which assisted Galileo to elucidate the laws of motion and lay the foundations of dynamics. There are very many other instances. The resources of arsenals assisted Lavoisier to conduct his famous researches in chemistry and physiology, and Rumford to make his on the relations between mechanical work and heat. The invention and improvement of equipment has long been, and will always be, one of science's chief contributions to the technique of warfare. In the war of 1939-45, however, science entered in a new way ; scientific method was applied more consistently and deliberately to the use of weapons and the conduct of military operations.

The first identifiable starting point of operational research in its modern form seems to have been the study of the use of radar equipment. Before the war Rowe had interested himself very

particularly in the problem of using civilian scientists' knowledge in radiolocation, to help the fighting man in its proper use. With this end in view he, as Superintendent of the Telecommunication Research Establishment (then called Bawdsey Research Station), and Wing Commander R. Hart made an informal arrangement that on the outbreak of war—when T.R.E. was to move instantly to Dundee—a small group of T.R.E. scientists under Mr. H. Larnder should remain in the south and form a research section at Headquarters of Fighter Command at Stanmore. This group of scientists made itself so useful that when the period of their loan had elapsed, the Commander-in-Chief asked that some of them might be kept, and this was agreed. Other types of problem were gradually presented to the group, which acquired more staff to cope with them. Besides being the home of radar research and development, Bawdsey was also the birthplace of operational research. A feature of the initial successes of operational research was that they were achieved by junior scientists who had not yet received academic distinction or organizational recognition, but were men of high talent, zeal, initiative and imagination, working under the guidance of experienced scientists.

The feature of all work at Bawdsey was to extend the range of detection so as to give more time to deploy the defences. Time could, however, be bought in another way, by reducing the interval between the first warning and the deployment of the defences. It was necessary to integrate the growing radar system of early warning with the then existing system of operational control based mainly upon the Observer Corps. Some aspects of this problem were those of a communications engineering character. For a complete study, however, a close inside view was needed, and a detailed knowledge of how the new information could tie in with the existing system of operational control in groups and sectors. Mr. G. A. Roberts, a scientist with previous experience of communications engineering, was assigned to do this job by the Superintendent, Bawdsey. By the outbreak of war he had carried out several investigations into the total efficiency of the communications system including problems of the organization and the rate and manner in which all available information was supplied and tied together. He had stepped outside the boundaries of communications engineering, equipment, electrical circuits, and all the physical paraphernalia, and had entered into the wider field of the executive officer responsible for the control systems as a whole. Most of his recommendations were eagerly adopted by the R.A.F.

In the meantime the number of early-warning stations had been growing and it was becoming known that there was substantial

variation in performance between them even when operated by the same group of test operators. At the same time with the spread of the number of stations there was an ever-growing number of operators, and variation in skill of the operators was suspected as being an important factor in the variation of performance of stations. Dr. E. C. Williams commenced a comprehensive analysis of the performance of these stations. By comparing the best with the worst and finding out the reasons for differences he was able to recommend methods of improving operators' technique. In addition, however, hitherto unappreciated limitations in the network, some of them due to local geographical conditions, were brought to light and these were made known to the R.A.F. To be forewarned was to be forearmed.

Recognizing the importance of the work of Roberts and Williams and noting that it touched at a large number of points, the Superintendent, T.R.E., brought these two together in a section under Larnder. On the initiative of Air Commodore K. R. Park, now Air Chief Marshal Sir Keith Park, then Senior Air Staff Officer at Fighter Command, arrangements had been made for its transfer to H.Q. Fighter Command at Stanmore in the event of war, and on September 3rd, 1939, the section took up its duties there, where it soon became known as the Stanmore Research Section. They were still responsible to the Superintendent, T.R.E., but they were encouraged to regard themselves as part of the Command staff. Under Larnder's direction the section steadily extended its scope of activities beyond radar and its uses, and by the time of the Battle of Britain, was consulted on an ever-widening variety of subjects, including battle wastage rates, harmonization of guns, etc.

During the period before the Battle of Britain there was some German night activity, sporadic bombing, mine-laying, etc. Our night fighters were equipped with airborne radar A.I. (Air Interception) which enabled them to engage in combat once they had been brought by radar control from the ground to within the range of the A.I. From a study of these operations the research section found that it was necessary to improve the method of getting to within the A.I. range, and they suggested to T.R.E. that some system of Ground Control Interception (G.C.I.) was necessary. This was the main reason for the crash programme for the adaptation of existing equipment which was undertaken and proved so invaluable in the night raids of early 1941 ; but G.C.I. also served as a reserve machinery for control in the event of the main system being put out by enemy action, a need which had been outlined by other operational research section investigations. During the night

attacks the section undertook a detailed and comprehensive analysis of all phases of night operations and presented the Command staff with an analysis of the performance of A.I., G.C.I., various forms of night interception, including co-operation with searchlights, the effect of visibility conditions, etc., the proportion of interceptions resulting in combats and of combats resulting in kills. This was used in the Secretary of State for Air's Scientific Committee and the Prime Minister's Night Air Defence Committee, and subsequently became the pattern on which other Operational Research Sections' analyses of current operations were based.

By the summer of 1941 operational research was recognized as an important activity by the Air Ministry and it was decided to set up Operational Research Sections very widely in the R.A.F. The Stanmore Research Section became in consequence the prototype of all the other sections and was re-named Operational Research Section, Fighter Command ; and Larnder, its first head, was given the title of Scientific Adviser to the C.-in-C. Fighter Command. These three rank-and-file workers from T.R.E. were the first to apply in practice scientific method to general staff problems in a military command.

The original trio, with three more junior members of the Stanmore Research Section, Cole, Bower, and Egner, were at one time or another between them Officer-in-Charge of Operational Research Sections at Fighter, Coastal, Middle East, India and Air Command S.E. Asia, A.E.A.F., Mediterranean, Transport, Flying Training Commands and the Royal Australian Air Force.

There had already been a radar off-shoot working in Coastal Command. Kendrew was advising on the use of radar equipment installed in planes to assist in the direction of ships, convoys and submarines at ranges beyond that of the naked eye and in darkness and conditions of poor visibility. This radar equipment was known as A.S.V., as it sent radiolocating waves from the aircraft to the surface vessels. Blackett had come to Coastal Command in March 1941 as Scientific Adviser to the C.-in-C. There two streams came together under Blackett who became head of the Operational Research Section at Coastal Command.

At Bomber Command, Dickins of the Directorate of Scientific Research at the Air Ministry had been studying pilots' reports on the enemy's defensive measures against our night bombing and had been writing monthly reports on the subject for some time. Earlier still, before the war, he had been associated with the development of fighter control systems at Biggin Hill. He was invited to become the first head of the Operational Research Section at Bomber

Command where he remained for the duration of the war. The staffs for the Operational Research Sections were provided by the Directorate of Scientific Research at the Ministry of Aircraft Production, who shared the work of co-ordination of operational research with Operational Research Centre at Air Ministry. The head of the centre later became the Deputy Scientific Adviser to the Air Ministry. Under him, at various times, besides the three operational centres already mentioned, new ones were created at other headquarters, such as Middle East, S.E. Asia Command, 2nd Tactical Air Force, Transport Command, Flying Training Command, etc.

Operational Research in the Army started through the fact that anti-aircraft gunnery was an army assignment. Anti-aircraft Command was under the operational control of Fighter Command in the Royal Air Force, but was an Army Command. In September 1940, it became clear that air attacks on London would frequently be made by aircraft invisible, even with the aid of searchlights, from the ground. A radar equipment for gun-laying, which determined the bearing and the slant range of an attacking bomber was already in use. This was named the G.L. Mark I equipment. It did not, however, give the elevation of the attacking aircraft. This was provided by a sound-locating apparatus. The combination of equipments for controlling the aiming of the guns was very cumbersome, and seldom worked. In fact, the system could hardly be dignified by the term " Fire Control." When it failed, the batteries resorted to a barrage, based on an estimate of the future position of the aircraft obtained by rough plotting of radar data. This was so inaccurate that it could be regarded as little more than a gesture of fist-shaking. Nevertheless, the system increased the efficiency and decreased the fatigue of the gun crews.

Fortunately, the radar scientists had already produced a modification of the Ground Controlled Interception apparatus which also gave the elevation of the aircraft. This was substituted for the sound-locators. But the combination of the bearing with the elevation-finding equipment was also delicate and uncertain in its behaviour. It would not give satisfactory results unless it was adjusted to the limits of its capabilities, and even then it gave inaccurate results for which there was no adequate explanation. It was evident that ordinary anti-aircraft gunners could not be expected to operate such difficult equipment. In August 1940, General Pile, the Commander-in-Chief, Anti-Aircraft Command, sought scientific aid and Hill recommended him to secure Blackett as his Scientific Adviser. After examining the situation, Blackett

advised that scientists should be secured to put and keep the apparatus in order and to reside on the gun sites. Oscillators were hung from balloons to send out radio waves which would simulate the radio echoes from planes, and this he used for testing the gun-aiming equipment.

As Anti-Aircraft was an Army Command, it was the duty of the Ministry of Supply to find the scientists. Cockcroft was asked by Dr. H. J. Gough, the Director-General of Scientific Research and Development of that Ministry, to organize their training and work. A school was established at Petersham in November 1940, under Ratcliffe, and sixty scientists were given a quick training in the use of the radar equipment.

A new point had emerged. Radar apparatus that worked perfectly in the testing-laboratory often failed to work properly on the sites where it was erected. Thus the traditional method of proofing equipment did not completely apply to the new apparatus. An ordinary gun-sight behaved in the same way in the workshop as in the battlefield. Thus the scientist who tested it need not leave the workshop. He did not need to inspect it on the battle-site. He could do everything in his power without leaving the depot. This would not work with radar gun-sights, for they were " temperamental," and were affected by their neighbourhood. Blackett saw that the necessity for using the completely new technique of controlling the fire of anti-aircraft guns at fully unseen aircraft would present many new problems which would need scientific study on the spot. In mid-September 1940, he decided to bring together a number of men with good scientific training but without specialist radio knowledge, to study the new problems from a more general point of view. They were to study the performance of the gun control equipment in the field, especially during its actual use by the troops against the enemy. The first two members of this group were physiologists, the next two were mathematical physicists, then an astro-physicist, followed by an Army officer, an ex-surveyor who, while he had been in the Derby-Nottingham area, had shown much originality in devising a barrage based on radar slant range measurements. The team was later completed with a third physiologist, a general physicist and two mathematicians : it apparently established its title of Anti-Aircraft Command Research Group by making a rubber stamp with the initials A.A.C.R.G. It is not known whether any more formal authorization or recognition was ever obtained.

The group became known as " Blackett's Circus." One of their first investigations was the correlation of the errors in aiming of an

accurately adjusted radar equipment with the slope, surface and nature of the ground, the presence of metal Nissen huts, etc., about the site. It was suggested by Bedford of A. C. Cossor, Ltd., that the ground around the radar receiver should be covered by mats of wire-netting which would provide a level uniformly-conducting artificial ground surface. Professor N. F. Mott calculated the area of the netting, and the best size of mesh. When these mats of wire-netting were fixed over the ground around the radar receiver the grass often grew under them luxuriantly. One commanding officer introduced geese to keep the grass down, and made a stir by applying for twelve A.T.S. girls to look after the geese.

The members of the " Circus " were frequently on the gun-sites during the nightly attacks on London. The tracking of the enemy bombers by radar revealed data on their tactics. The scientist began to study these data systematically.

In Coastal Command, a similar development occurred about a year later, when the Commander-in-Chief thought it advisable to have scientists at his headquarters who could study and advise on the use of radar equipment being installed in planes to assist in the detection of ships, convoys and submarines at ranges beyond that of the naked eye, and in darkness and conditions of poor visibility. This radar equipment was known as A.S.V., as it sent radiolocating waves from the aircraft to surface vessels.

In March 1941, Blackett moved from A.A. Command to Coastal Command. The members of his " Circus," together with Ratcliffe's colleagues at the Petersham Anti-Aircraft Wireless School, and some others, were presently organized as the Army Operational Research Group. Brigadier B. F. J. Schonland, the South African physicist, became Superintendent, and the Group, which had arisen out of the application of the technique of science to the study of anti-aircraft defence, extended the application to the general study of military operations, chiefly with regard to the utilization of equipment and weapons. It developed into eight sections, concerned with Anti-Aircraft Defence, New Radar Equipment, Signals, Field and Anti-tank Gunnery, Army Air Operations, Infantry Operations, Lethality of Weapons, Land Mines, Obstacles and Special Weapons.

Blackett's work at Coastal Command brought him into very close contact with the problems of the anti-submarine war, and with the Admiralty. He brought a professional, besides a scientific, interest to the study of naval problems, having formerly been a naval officer. He was appointed Director of Naval Operational Research at the Admiralty in December 1941. Thus he had a primary part

in the establishment of operational research in the Army and the Royal Navy, and a leading part in its development in the Royal Air Force. Blackett was succeeded at Coastal Command by the late Professor E. J. Williams, who did brilliant work on the setting of depth charges, the Bay of Biscay offensive against U-boats, and other problems.

Parallel with these developments in the Services, a similar one occurred in the civilian defence department, the Ministry of Home Security, whose Director of Research and Experiments was Sir Reginald Stradling. This Ministry had a Civil Defence Research Committee, which included among many distinguished members, Professor J. D. Bernal. When the war started, Bernal and many of these scientists immediately joined the staff of the Ministry's research organization. They greatly extended the experimental and theoretical knowledge of explosions, and of their effect on buildings and structures, and on animals as a guide to their effects on human beings.

When the heavy bombing of British cities and factories began, Bernal introduced the comprehensive collection and study of the statistics of damage done by the enemy bombing. Stradling organized a field staff to collect the statistics of damage from the bombed areas. The nucleus was provided by the staff of the Cement and Concrete Association, whose advisers and salesmen were established in the main centres in the country, and had excellent local connections and were used to working together. They were able to bring a personal informality into their inquiries. This is essential in questioning victims and persons whose homes and property have been damaged. There were 120 observers in the field, and 40 at headquarters to analyse the information collected.

All kinds of rumours were in circulation as to the effects of bombs on human beings. At the beginning of the war it was officially believed that human beings would be killed if struck by a blast pressure of 5 lb. per square inch. The anatomist and authority on monkeys, Professor S. Zuckerman, was invited to investigate the effects of blast on living organisms. He placed goats in trenches, exploded bombs just outside, and found that the goats survived. The goat has about one-third the weight of a man, so it was possible to make a reasonable deduction, from the effect on the goat, what would be the effect on a man. Zuckerman found that a man should have a 50 per cent chance of survival when struck by a blast pressure of 500 lb. per square inch. He showed that blast was in fact one hundred times less dangerous than had been supposed. This discovery revolutionized conceptions of the effects of bombing.

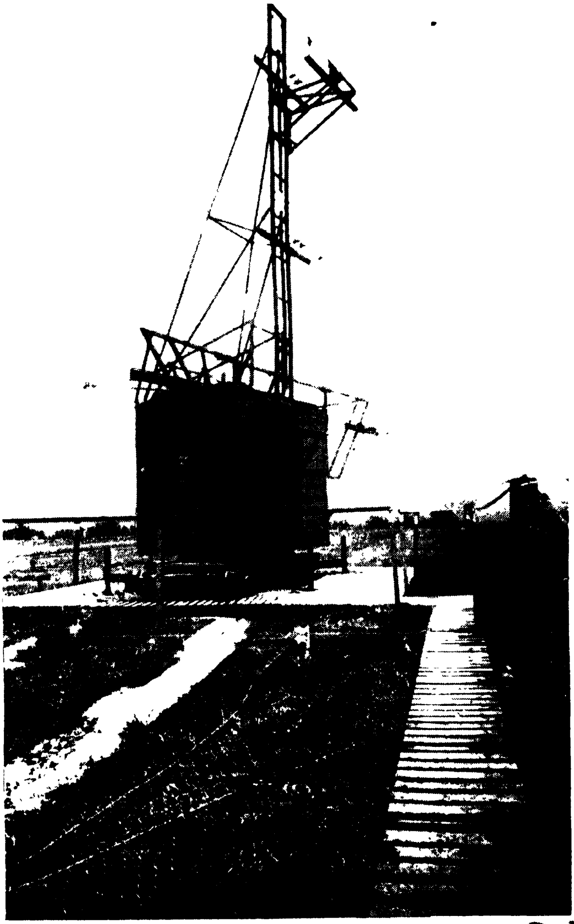
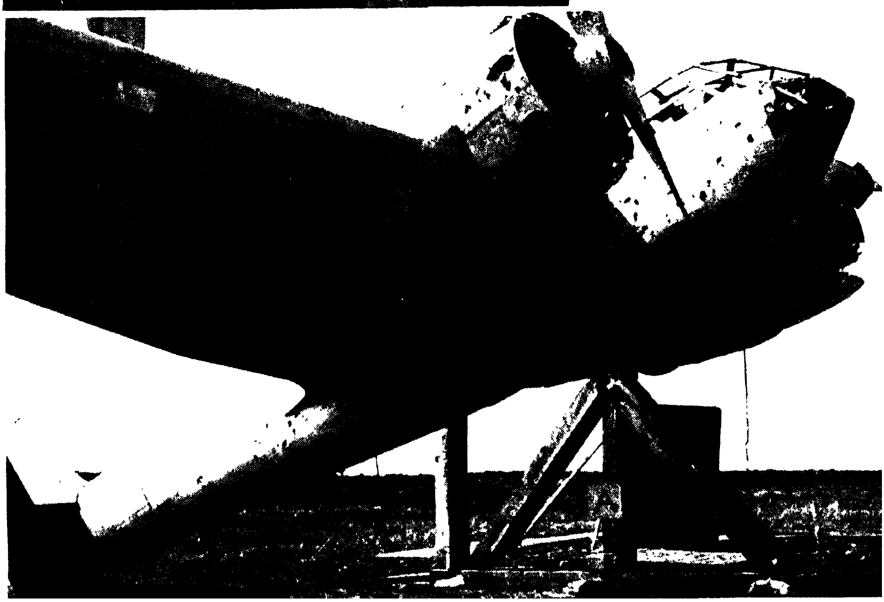


PLATE XXXIII

Wire-netting used in early anti-aircraft radar equipment to eliminate interference with the radio waves of irregular reflections from uneven ground.

PLATE XXXIV

Statistical investigations of the effect of shell bursts on an aircraft. By firing at aircraft on the ground, it is possible to discover the average number of hits by fragments required to put the aircraft out of action.



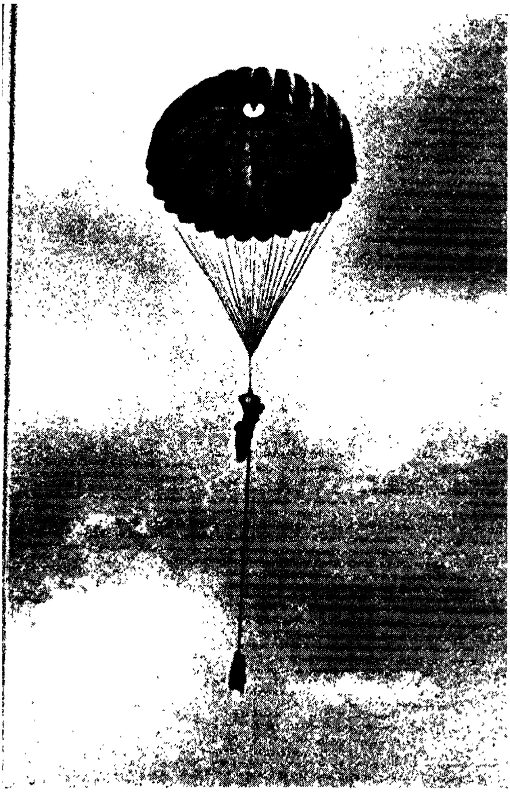


PLATE XXXV

Finding out exactly what happens during parachuting. When the paratrooper jumps his kitbag is attached to the lower part of his leg, to keep it out of the way of the rest of his tackle. The kit-bag is then dropped from the man, but drags a rope 20 feet long, the other end of which is attached to his harness. When the rope is fully outstretched, it receives a jerk, and is liable to snap. A shock-absorber or snatch-eliminator is used to reduce the jerk.

In the picture J. Izard is seen testing one of the shock-absorbing devices that he has introduced. He overloaded a normal kit-bag weighing 60 lb. to 90 lb., and then jumped with it attached to the normal position on his leg. When the parachute properly opened, he released the bag to the full extent of the rope and used the snatch-eliminator to reduce the jerk.

Izard has also made a study of parachute oscillation and determined the optimum length of kit-bag ropes.

This kind of operational research involves considerable personal risk to the experimenter.

PLATE XXXVI

What it is like inside the turret of a tank five seconds after a shot from a flame-thrower.

The tank turret has been detached and mounted on the top of a German Tobruk shelter. The photograph was taken from inside the shelter looking up at the turret ring. This involved the photographer in considerable risk. He remained inside the shelter only for the moment necessary for taking the photograph.

On the left is a thick almost vertical band, which is a cloth pole wound with battle-dress serge, in order to see the effects of the flame on it. To the left of the pole is a wire grid protecting the platinum resistance wire of a pyrometer for measurement of the internal temperature. The dark parts on the right of the centre of the picture are parts of the gun mounting.

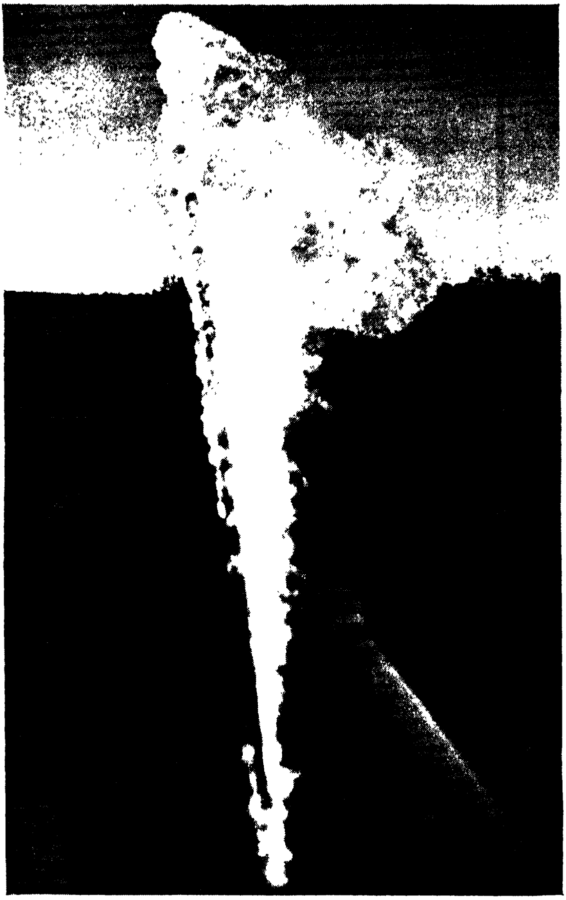


PLATE XXXVII

Operational research on flame-throwers. Research was carried out on the most suitable form of jet and composition of the fuel, in order to obtain the greatest effect at the greatest range. The results of this research were then tried out in the way shown in these photographs. The jet of the flame-thrower as seen from the carrier tank is shown on the left. The fuel remains largely unburnt for a considerable distance after leaving the nozzle. Below an experimental trench is seen during an attack. The effects of each attack were assessed by the damage done to pieces of battledress serge placed over the bottom of each trench, by pyrometer readings in selected trenches and by visual and photographic observation.

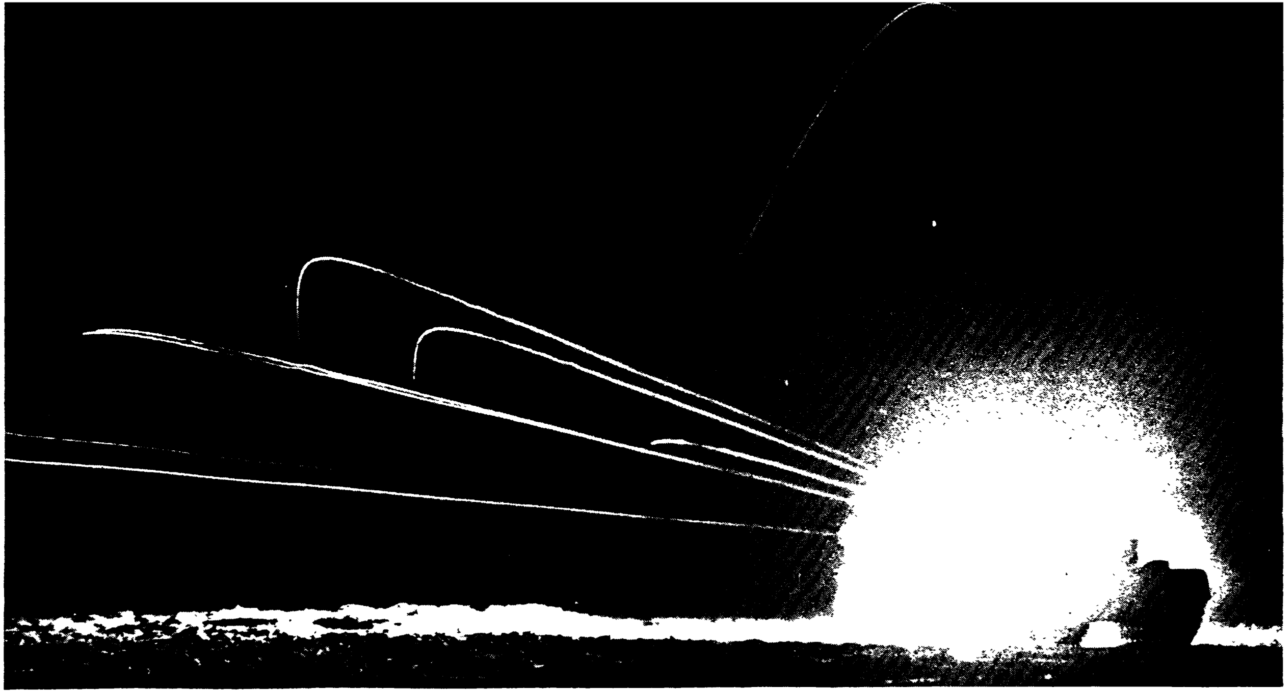


PLATE XXXVIII

Trace from a six-pounder armour-piercing shot. Tank guns fire solid shot when attacking another tank. These shot are fitted with a " tracer " which emits a bright flame in flight. The development of very high muzzle-velocity guns during the war has provided many problems for research. What is the most suitable colour? Do colour filters help in daylight observation? Can " trace " dazzle at night? What hope is there of significantly increasing the brightness for use in daylight? And other queries require answers.

Operational research is a necessary part of the research required to answer such questions.

In this picture, " tracer " shot are being fired at a rocky hill from a six-pounder in a Churchill tank. The trace is very bright. Two shots have passed over the brow of the hill, while one has hit a rock and ricocheted upwards at a high angle.

Zuckerman organized a group of medical observers to collect information on the medical injuries actually occurring during bombing. This agreed with the information gained from the experiments. He developed the conception of a standardized casualty rate from the statistical and experimental data. He was able to forecast with a considerable degree of accuracy the average number of casualties which would occur if one ton of bombs was dropped on one square mile of territory of given population density. In June 1940, Bernal and Dr. F. Garwood forecast the results of a raid by 500 enemy bombers on a typical English town. They happened to choose Coventry. They worked out what the effects would be from new data of the destructiveness of bombs, and their probable distribution on the town, as determined by statistical experiments. Some time afterwards, Coventry was attacked by about 500 bombers in the notorious raid. The forecast by Bernal and Garwood of the amount of damage and casualties was exactly confirmed when the results of this serious attack were surveyed. This feat gave the conception of a scientific bombing attack on Germany a new degree of reality and accuracy.

The results of these investigations in 1940-41 became a guide to future bombing policy. Thus it became possible to base the offensive on the analysis of experience gained in the defensive. The civil defence organization had got the most recent data on what modern weapons could actually do. When the possibility of a British bomber offensive came to be discussed, they were asked whether they could estimate what such an offensive might do. By a splendid effort of the mind, the enemy's attacks were turned against himself, through knowledge gained by analysis of their results. The defensive became the guide to the offensive.

Bernal became Scientific Adviser to the Combined Operations Command, and Zuckerman Scientific Adviser on Planning to the Allied Expeditionary Air Force in 1943.

Applications of Operational Research

We have sketched how operational research was born and grew to a formative influence on the strategy and tactics that won the war. A few examples out of thousands of cases will help to illustrate the procedure.

At the beginning of the war, Coastal Command had disappointingly little success in air attacks on submarines. They first used an

anti-submarine bomb, and then changed over to standard 450 lb. depth charges, following this with a special 250 lb. design. The latter could be safely dropped from a very low height, but still little success was obtained. A study of the operation revealed in the spring of 1941 that the depth charges were set to explode at depths of 50 to 150 feet, which was far too deep. The settings had been chosen on the assumption that when a submarine is attacked from the air, it will have seen the approaching aircraft and will have dived to a depth of from 50 to 150 feet during the time that the aircraft takes to catch up with it. A setting of about 100 feet was therefore recommended.

The operational researchers, led by E. J. Williams, investigated what actually happened. They found that when the plane caught up with the submarine, the latter was, on one occasion in every three or four, at or near the surface. It was visible or had only just disappeared, and therefore could be attacked with maximum accuracy. In the cases when it was not visible and had dived deep, its position was already very uncertain one minute after starting to dive, owing to turning movements executed under the water. Thus it was advisable to concentrate on hitting the submarines still at the surface or which had not been submerged for more than 15 seconds, as they were much easier targets.

Calculation showed that the best setting for the exploding of the depth charge was probably about 25 feet. But the mechanism for detonating the standard depth charges (termed the " firing pistol ") could not be set for depths shallower than 35 feet. Being at the moment unable to do better than this, the researchers advised setting the charges to explode at the minimum depth of 35 feet. The number of submarines sunk or killed in proportion to air attacks went up from two to four times. This increase in effectiveness was obtained almost at once, without years of research and development of new weapons. The research also showed the need for a depth charge with a 25-foot setting. This was not easily met, for when the depth charge enters the water an air cavity is created behind it, and the firing pistol is apt not to come in contact with the water. The problem was solved by the R.N. Mines Department's designing the shape of the depth charge so that the part of its case carrying the firing pistol would slap against the water side of the air cavity, and thus be fired at 25 feet. Prisoners taken from sunk submarines shortly afterwards told their interrogators that they believed we had doubled the amount of explosive in our depth charges and that this was the cause of the increase in sinkings.

THE OPTIMUM SIZE OF CONVOYS

When convoys of merchant ships were mass-attacked by U-boats in 1942, they were liable to suffer heavy losses. The average size of convoys at that time was about 40, and they were protected by six escorts. It was estimated that, without air escort, about double this number of escorts would be necessary to provide adequate protection. At that time extra escorts did not exist, so that planners had to see whether any other improvement could be made. The only variable in the situation which the planners could change at will was the size of the convoy. Following this idea, they investigated the losses that had actually occurred in convoys of various sizes, and found that in 1941 and 1942 the percentage losses in large convoys were markedly lower than in small convoys. Of all ocean convoys sailing in the period from January 1941, to April 1943, those with less than 45 ships lost on an average 2.6 per cent of their ships, while those with more than 45 ships lost on an average only 1.7 per cent. In fact, about the same number of ships were lost per convoy, whether the convoy was small or large. It was found, too, that the number of escort vessels for both small and large convoys had been about the same, and the size of the attacking U-boat packs had also been fairly uniform.

The reason for smaller relative losses in big convoys is probably the fact that the perimeter of a large convoy is only slightly larger than that of a small one, because the area occupied by the ships increases as the square, while the perimeter is directly proportional to the length, of the radius. Hence the number of escort vessels needed to watch the perimeter of a big convoy is almost the same as that needed to watch the perimeter of a small convoy. For instance, if the escort vessels are to be out at a distance of 4,000 yards from the convoy, the perimeter for a convoy of 80 ships would be only one-seventh longer than that of a convoy of 40 ships. Thus seven escort ships can protect a convoy of 80 as well as six escorts can protect a convoy of 40. If a submarine breaks through the escort screen, it is improbable that it will sink more ships in the big than in the small convoy because it will have in both cases the same limited number of torpedoes. Its position will resemble that of a man out duck shooting : if a flock of 80 duck fly over him, he will not be able to shoot down any more than if a flock of only 40 birds fly over ; for he will be able to fire only the same number of shots in both cases. He will not have time to re-load. Neither is the submarine able to return to base, re-load, and re-attack, after it has fired its store of torpedoes.

For similar reasons, under individual submarine attacks, large convoys without any escort protection at all are less expensive than individual sailings of single ships. When the U-boats attacked the American shipping off the east coast of the United States after December 1941, they inflicted severe losses for a considerable period. The ships were then sailing individually, and were attacked individually. If the American merchant ships had sailed in large groups, even without any protection whatever, the total sinkings would probably have been reduced. Suppose, now, that a certain freight programme has to be carried out, which requires a convoy of 50 ships to leave every eight days from each side of the Atlantic. The same amount of freight could be transported by convoys of 75 ships leaving every 12 days. This would reduce the crossings by one-third, and the reduction in the number of U-boat attacks would be almost as great.

In the summer of 1943 there were 11 groups of escort vessels in the North Atlantic for close protection of convoys. In addition to these, three groups of supporting escorts were held in reserve for going to the relief of attacked convoys. By reducing the number of convoys by one-third, enough close-protecting escorts could be released to form three more groups of supporting escorts. Thus the number of close-escort groups would be reduced from 11 to 8, while the number of support groups would be increased from 3 to 6. Hence the chance of an attacked convoy receiving relief from a support group of escorts would be approximately trebled, for the chances of a convoy being relieved by a support group of escorts is 3/11 and 6/8 respectively, or about 3 to 1 in favour of the large convoy plan. This work was largely due to Dr. H. R. Hulme and Mr. J. H. C. Whitehead.

Making a Little Go a Long Way

When data on various types of operations have been collected and analysed, it is possible to think quantitatively about the best way of allocating existing resources.

In the early days of the war when U-boats were operating near our shores, aircraft were used for escorting our convoys. As our defence measures improved, the U-boats were forced to operate further and further out into the Atlantic, and our aircraft had to follow them very far out into the ocean. In the autumn of 1942, some very long-range aircraft were introduced, which enabled air escort to be given to a convoy anywhere in the Atlantic. But at the beginning, the number of these special aircraft was quite inadequate to provide air cover to all the convoys all the time.

The Germans' submarine campaign had not been very successful in the first year of the war. Our system of convoys, with escort vessels aided by detection devices, had dealt fairly satisfactorily with individual U-boat attacks. In the autumn of 1940, the enemy made a major innovation in the tactics of submarine attack. He replied to the protected convoy with the mass U-boat attack. The primary advantage of the convoy is that it greatly reduces the number of sightings of ships by submarines, thus causing many U-boats to return to base without having fired all or even a large part of their store of torpedoes. In the new system of attack, a U-boat which sighted a convoy did not attack forthwith, but reported to base, which at that time was in France, the course and speed of the convoy. The U-boat Command then directed ten, or even, once or twice, as many as thirty U-boats, to attack the convoy simultaneously. Thus one sighting of a convoy produced not one attack by one submarine, as formerly, but many more attacks by numbers of submarines. The German operations depended on a highly organized radio communication system between the U-boats and their base, and Doenitz was in minute-by-minute control of actions far out in the Atlantic. The U-boats attacked on the surface so as to be as free as possible from detection by underwater ultrasonic means, and at night so as not to be visible. Their speed on the surface was as much as 18 knots, whereas that of the corvette escort vessels was at the time about 14 knots. They did great damage, sinking sometimes as many as 12 ships in a night, and a total of 20 out of one convoy during an attack lasting several nights.

Air escort had for long been found to be an important element in the defence against U-boats. The analysis of the loss of ships in the second half of 1942 showed that air cover for eight hours a day during attacks reduced losses by 64 per cent. One merchant ship was saved for every three aircraft sorties. As each very long-range aircraft made on the average 40 sorties, before it became a casualty itself, it was able on the average to save 13 ships while these particular conditions lasted. The effect was so large because the U-boats had to remain on the surface in order to keep up with the convoy. When sighted by the aircraft they were forced to submerge and lose speed and hence lose touch with the convoy, and had great difficulty in finding it again. This particular use of aircraft during this period was one of the most profitable operations at sea ever carried out. So much for the importance of giving air cover to convoys. Naturally, the enemy tried to evade this by attacking further and further out. This increased the proportion of time spent by the aircraft in travelling to and from the convoy—dead time, so to

speak—and so reduced the time spent around the convoy. This meant that for any number of hours' flying around the convoy more and more planes were needed. Moreover, the battles now took place beyond the range of our main aircraft types, and eventually the very long-range aircraft (V.L.R.) were introduced in the autumn of 1942, but they were few in number. One result of these researches was to emphasize the importance of attacking the U-boats while they were in transit across the Bay of Biscay.

Most of the other examples of operational research quoted have been instances of where the scientists played a major and initiating role in the development of tactics. This particular aspect of the U-boat war has been quoted more because of its great general interest than because of the outstanding part played by the Operational Research Sections. It was particularly a Command development. It is interesting for another reason. It was an early example of the problems of deciding how to apportion limited resources so as to achieve maximum results. This was later extended into measurement of cost in terms of crews' lives, man-hours of work, etc., to achieve certain results. Had we then had our present knowledge and sophistication, an analysis would have been made, against the appropriate time-scale, of the effectiveness of convoy escort, U-boat patrols in the Bay, the bombing of U-boat pens and Biscay ports, to decide what method or combination of methods would secure the maximum saving of shipping with the resources available. This particular case, in combination with the new knowledge of costing that arose from the developments outlined in the next section, also led to a detailed comparison of the relative usefulness of various aircraft types. This, however, came too late in the war to affect the production programmes, though, if taken earlier, it would have had a major effect on production policy.

GETTING MORE OUT OF AIRCRAFT

It is economical to get the maximum amount of use out of any kind of equipment, and essential when there is a shortage in supplies.

The growth of the U-boat offensive, based on the Bay of Biscay, became very serious in 1942, and the need for increasing the weight of our depth-charge attacks on the U-boats became imperative. The ways of using our available aircraft were carefully analysed and it did not seem to be possible for them to be used more efficiently. Dr. C. Gordon, a member of Coastal Command Operational Research Section and formerly a geneticist from the Department of Natural History in the University of Aberdeen, was requested by E. J. Williams to examine this problem. He approached it from

the natural historical point of view. He studied one flying-maintenance cycle of aircraft as if he had been studying any biological system. He recorded what actually happened in the flying routine of Coastal Command. As a biologist trained in statistical analysis, he was in the habit of deducing from first principles what kind of relationships should exist among the various aircraft "states" shown in the records. His investigations showed that lack of air-crews or shortage of any particular item of equipment were not the cause of the failure of aircraft to patrol more often; so a careful examination was made of what happened to an aircraft when it was on the ground. Unlike a good motor-car the modern aircraft needs constant careful maintenance, thorough frequent inspections, adjustments and repairs. The efficiency of the R.A.F. largely depends on its maintenance system. This was examined, and its criterion of efficiency queried. What did this mean, and was it adequate? Now the criterion of efficiency was what is called the serviceability percentage; that is, the number of aircraft serviceable and ready for operations together with those operating, expressed as a percentage of the total number of aircraft. The maintenance organization had always aimed, and with success, at keeping this percentage as high as possible. The worth of this criterion was then examined. The accepted desirable figure was 75 per cent. Calculations based on the total rate of arisings of maintenance work per hour of flying showed that if all aircraft were flown whenever serviceable, approximately one-third would be airborne at any particular time, and two-thirds would be on the ground undergoing maintenance. The maximum number grounded under the old system was, in fact, nearer one-third. The achievement of the lower number of aircraft grounded, that is, the high serviceability of 75 per cent was only by curtailing flying; and this meant that only a portion of the serviceable aircraft were flown under the old rule. In fact, the only way in which all aircraft can be kept serviceable is never to fly at all. The conformation of the serviceability figures to the official requirements proved, firstly, that in fact more flying could have been obtained and, secondly, that the accepted criterion of maintenance efficiency was invalid. To prove these results a squadron was ordered, as an experiment, to disregard the serviceability percentage and fly as much as it could whenever aircraft were available. The flying output was doubled, the serviceability percentage sank, and the maintenance system continued to function satisfactorily. Indeed, this last was considerably strengthened by organizational improvements which the experiment had suggested, and by the invention of new criteria of efficiency which drew attention to potential bottle-necks in maintenance

organization. The overall criteria of efficiency became the proportion of serviceable aeroplanes flown on each day of operational opportunity, and the flying-hours per maintenance man. If one squadron could double its flying output by a better use of its existing resources, namely, aircrews, aircraft and maintenance men, then there was reason to believe that the lesson so learnt would be generally applicable. This proved to be true ; and the Command eventually achieved approximately 100 per cent increase in its flying output. This meant that more patrolling was done, more U-boats were sunk, and Coastal Command made a much greater contribution than hitherto in the Battle of the Atlantic.

BOMBER LOSSES

The causes of losses of bombers were investigated by the Operational Research Section of Bomber Command. The losses suffered in attacks on Cologne and Frankfurt were analysed. The relation between the number of aircraft used in a given area, that is, the concentration, and the losses suffered, was investigated, both for operations in moonlight and in the dark. The number of planes which could most efficiently be used per hour, or per minute, was deduced. The results, which were worked out in 1941, were in favour of highly concentrated attacks, and led to the introduction of the 1,000-bomber raids.

One of the objections to very big highly concentrated raids was the fear of collisions between the bombers in the air over the target. This problem was analysed by the Operational Research Section, who forecast that, on the average, one bomber per thousand might be lost through collision in such a raid. Subsequently, in the first 1,000-bomber raid on Cologne, one plane *was* lost by collision. This identical agreement with the operational forecast was, of course, a coincidence, but it strengthened confidence in operational research.

Many different kinds of bombing problem were analysed. Operational Research were consulted on any special bombing operation. For instance, they were asked to recommend how many aircraft, with what kind of bombs, should be sent to attack the *Tirpitz*. They forecast that thirty planes would be the most suitable number, and that they would probably score about three direct hits. Three direct hits were actually obtained.

The most efficient methods of stocking aircraft with ammunition were worked out. At the beginning of the war, aircraft took large loads of .303 machine-gun ammunition, on the principle that " they had better have all they can carry." The use of this ammunition

was analysed, and it was discovered that many rounds were fired in anger and frequently many were not fired at all. It appeared that aircraft habitually took excessively large quantities of ammunition which they could not use. Often, as much as 3,000 rounds, weighing about 500 lb. were merely taken for a ride. The carrying capacity could, of course, have been used for extra radar or other equipment.

A large investigation was made into the relative part played by enemy fighters, accidents, fire, and flak, in causing bomber losses. Light on the number of losses due to flak was gained by shooting at experimental aircraft on the ground. It was found that for every hundred holes in the aircraft of a group, one of that group was thereby destroyed. From this, it was possible to deduce the losses from flak that had probably occurred in a particular raid from the average number of flak holes made by shell fragments found in the returned planes. Suppose, for instance, that 100 bombers make a raid, and the 70 that return have an average of 10 flak holes each. Then the average for the 100 bombers would be about 10 flak holes, making about 1,000 for the whole group. One per cent of 1,000 is 10, so probably about 10 of the thirty that failed to return were destroyed by flak. The loss due to accidents could be fairly accurately estimated, as it would be much the same in other commands, where the fighting conditions would probably be different, allowing accident losses to be distinguished from losses due to other causes. The information collected by interrogation of crews was often very misleading. Gazing out into the night, under conditions of great strain, they were in the worst situation for providing objective evidence. Nor was much gained from the study of the enemy's claims of bombers destroyed.

The seriousness of the losses due to fire were emphasized by operational research, and led to increased efforts to improve fire prevention.

LAND FIGHTING

The methods of operational research, started in connection with aircraft, were applied to the study of the use of very many kinds of weapon, and the conduct of very many kinds of operation in the air, on the land and at sea. The extension of the method to the oldest kind of fighting, land fighting, is of particular interest. Fighting on land is more complicated than that in the air or at sea. The surface of the land is extremely variable, and the forces operating on it are often very large, varied and scattered. The air, on the other hand, is relatively a very uniform medium, and air forces

consist of a relatively small number of very condensed pockets. The sea also is uniform compared with the land, and sea forces also are concentrated, in ships. Hence operations in the air and at sea, though very complicated in themselves, are relatively simple compared with those on land.

The vast variety of operations and weapons used in land warfare offers an enormous field for operational study. For instance, it was found that shooting from a stationary tank at a moving target was not very effective, and was expensive in ammunition. Tank gunners in the field suggested that one important cause of inaccurate shooting was the heavy pressure that had to be applied to the trigger in order to fire the guns in British tanks. This pressure was equivalent to 25 lb. weight.

Shooting from Tanks

The Army Operational Research Group made an investigation to discover what effect variations in the pressure required to operate the trigger have on the accuracy of aim from a stationary tank at a moving object. They mounted a white board 2½ feet square on a scout car which could be run along an undulating road 400 yards long. The tank was stopped at a point at right angles to the road, and about 1,000 yards from its mid-point. The target was run along the road in three ways ; in the first at a steady speed of 10 miles per hour, then at a steady speed of 20 miles per hour, and then at a variable speed of from 10 to 20 miles per hour. Two gunners with ordinary training were secured to operate the tank gun. A camera was securely attached to the barrel of the gun, so that the accuracy of aiming could be automatically recorded. The gunner then went through the usual operations of loading, aiming and firing the gun, but working with dummy ammunition. The firing mechanism was arranged so that the pressure required to release it could be varied from 25 lb. to 65 lb. Two methods of aiming were used, the " following " method, in which the gun is made to follow the moving target, and the " laying ahead " method, in which the gun is aimed ahead of the target, then kept stationary, and fired when the target runs into the middle of the gunsight view. The gun may be swung round into the correct aim either by hand or by power. The trigger was arranged to operate at 25 lb. pressure, and then at 54 lb. pressure. The gunners went through the operations of aiming at the target, moving steadily at 10 miles per hour, by the "following" method; swinging the gun round horizontally, or in traverse, by hand. It was found that the chance of a hit, when the 54 lb. trigger pressure was used was 25 per cent less. At 20

miles per hour, it was 41 per cent less. The gunners then repeated the experiment, but used power to swing the gun. With the 10-mile-per-hour target, the probability of a hit did not decrease at all but with the 20 mile-per-hour target, it fell by 33 per cent. Next, the gunners fired at the target when carried at a variable speed between 10 and 25 miles per hour. It was found that the probability of a hit fell by 16 per cent when the gun was aimed by hand, and fell by 10 per cent when aimed with the assistance of power. These figures proved conclusively that increase in the load required to work the trigger caused a considerable decrease in accuracy of the horizontal, or traverse, aim, when shooting at a moving object. On the other hand, it was found that errors in the elevation aim were not increased by increase of trigger pressure. When the experiments were repeated with the " laying ahead " method of aiming, there was little significant decrease in accuracy with increase of trigger pressure. This was to be expected, for in this method of aiming the gun is moved into position and is stationary when fired. The gunner has to make fewer muscular operations, and the increase in trigger pressure does not interfere with him so much. As a result of these studies the Army Operational Research Group was able to recommend that it is absolutely essential that, if moving targets are to be aimed at accurately, the trigger loads of guns in tanks should be kept as low as possible, and should not in any case exceed 25 lb. If low trigger loads could not be guaranteed in existing equipment, then some other form of firing gear would have to be adopted. They recommended that, as a temporary measure, where trigger loads could not be reduced below 25 lb., gunners should be encouraged to use the " laying-ahead " method of aiming ; and that investigations should be made into the advantages of firing mechanisms operated by the foot instead of the fingers.

Laying Mines

In the late war the laying of mines was one of the principal defensive methods. Millions of them were laid, for tactical and strategical ends. It was therefore militarily important that the most efficient ways of laying mines should be discovered.

One aspect of this problem could be investigated by the technique of time-and-motion study developed in the organization of industrial production. The laying of a set, or panel, of mines one hundred yards long by a party of 30 men under an N.C.O., according to a regulation drill, was analysed by detailed studies of the component parts of the drill, by timing some of these with a stopwatch, and making a cinema film of the whole operation. In the regulation

drill, the operation was performed in three stages; the reconnaissance of the ground, the setting-out of the tapes along which

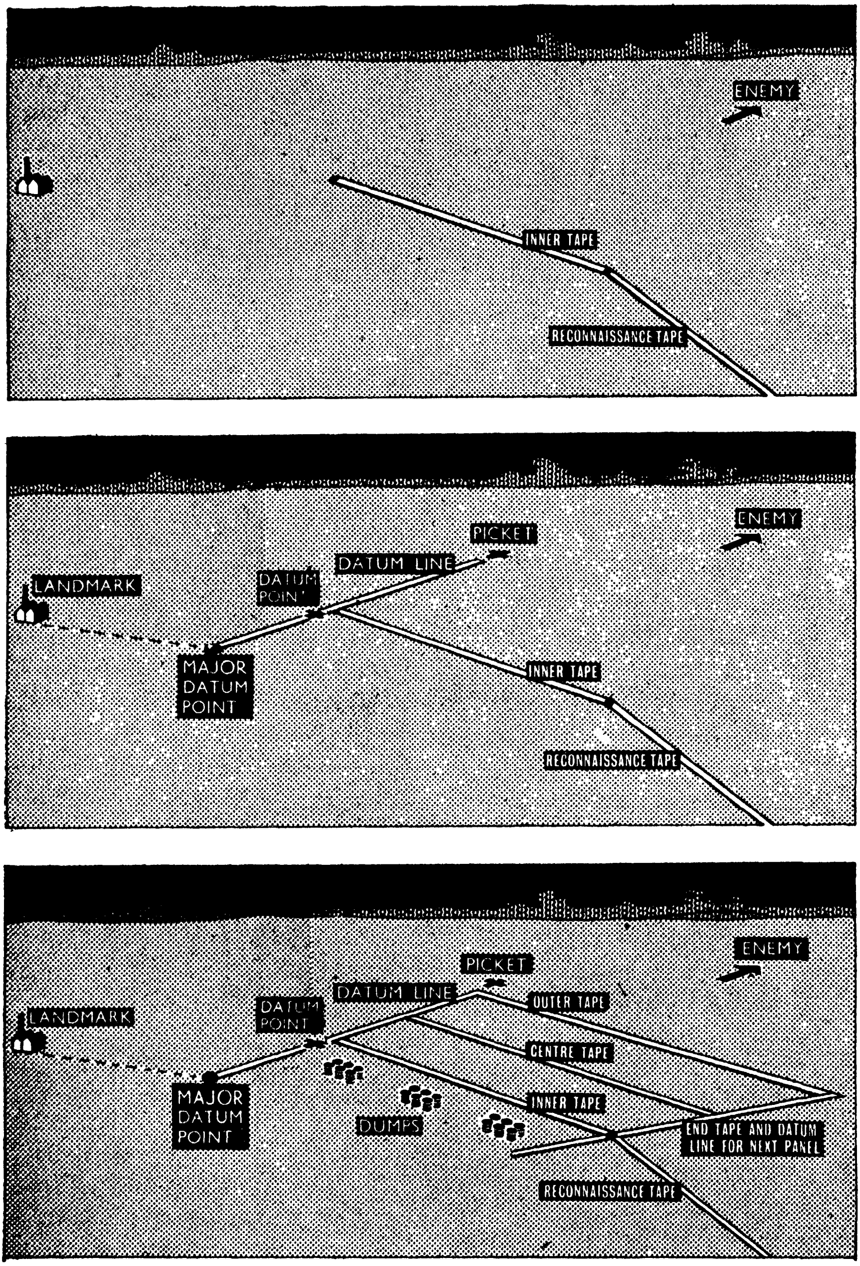


Fig. 38

the mines were to be buried, and the laying of the mines. The sequence of motions is indicated in Fig. 38. The reconnaissance of the ground is carried out by representatives of the laying party, and a tactical representative, who decide the layout of the field. They lay an inner tape to mark the inner edge of the panel. The setting-out party consisting of 8 selected from the 30 now arrive under the N.C.O. commander, who chooses a major datum point, and measures its distance and bearing from a neighbouring landmark. They then lay a datum line at right angles to the inner tape. All data are recorded by a " recorder " who accompanies the N.C.O. The setting-out party run tapes parallel to the inner tape, to an end tape which marks the beginning of the next panel of mines. In the meantime, the laying party may or may not have arrived on the site. If it has, it will build dumps of mines along the inner tape. Laying begins as soon as the setting-out is finished. The setting-out party consists of an N.C.O. commander, a recorder, and six other men, Nos. 1, 2, 3, 4, 5 and 6, whose tasks are : Nos. 1 and 2, to drive in three pickets and pace distance between tapes ; No. 3, to lay out datum and end tapes and peg down ; Nos. 4 and 5, to lay out laying tapes and peg down ; and No. 6, to lay out and peg inner tape, if the reconnaissance tape is not used as the inner tape. The analysis of the procedure showed that only the N.C.O. commander was employed all the time, while every other member was idle for some of the time. No. 6 was idle for all the time, as in practice the reconnaissance tape was always used as the inner tape. Nos. 3, 4 and 5 were idle for the whole period while the commander and recorder paced to and from the landmark. Nos. 1 and 2 were idle as soon as they had driven in the picket for the major datum point, which took them less than one minute. In the meantime, the laying party, consisting of 22 men, set up the dumps along the inner tape. They took about two minutes per dump, and then all of them were idle until the setting-out was completed. The actual working-time was only 53 man-minutes, while the total idle time due to all causes was 240 man-minutes. The regulation setting-out drill took the N.C.O. commander and his seven men 9 minutes 48 seconds. Of these, 3 minutes 10 seconds were entirely due to the time necessary for the commander to walk to and from the landmark.

Thus the analysers recommended that the measuring of the distance between the major datum point and the landmark should be left until after the laying party was at work, so that they could continue to bury mines while the commander walked to and from the landmark. This change alone would decrease the idle time to 134 man-minutes ; that No. 6 could be omitted from the setting-out party, which

would save nearly 10 man-minutes ; that by building dumps along all of the tapes, and not the inner tape only, 32 more man-minutes of the idle time of the laying party could be usefully employed instead of 14 man-minutes in the regulation drill. The analysers then worked out a new setting-out drill, in which a commander and four men could set-out a 100-yard panel of mines in 5 minutes 5 seconds. The laying party, when joined by the setting-out party after the setting-out is completed, will consist, of course, of all the 30 men. It was found that 30 per cent of the time of the laying party was idle. By recasting the procedure and duties so that, as far as possible, all of the men were working simultaneously, the total time for 30 men to lay a 100-yard panel of mines was reduced from 34 minutes 23 seconds to 26 minutes 11 seconds.

The Jap Trap

When the war in the Far East began, our troops reported that the Japanese put them under a constant strain by creeping up from any direction in the jungle at night. Some kind of simple warning device was asked for. An obvious device was a fine wire, which could be strung round the positions of our troops, and which would light a signal lamp when broken by an approaching enemy. It was necessary that the wire should be thin enough not to be noticed by the Japanese when broken and thick enough not to break accidentally. The appropriate size was determined by stringing wires across routes traversed by the large army of women cleaners found in all Ministry of Supply establishments either upright or on their knees with a scrubbing brush. These modes of motion were considered typical of Jap movement. Observers noted which wires were broken by the women cleaners without comment. A small current was sent through the wire, which kept a relay over one way while the current was running. When the wire was broken and the current stopped the relay went over and turned on the lamp.

Bird Echoes

The coastal radar listening equipments registered a variety of spurious echoes, in addition to those due to aircraft. They were of small signal strength, and appeared to come from objects moving at speeds varying from 5 to 80 miles per hour, often against the wind. Some of these were due to floating wreckage, others to drifting balloons. The great majority are as yet unidentified, but there is evidence that many were due to birds. In September 1941, a radar observer at Dover found that echoes appeared to be reflected from a number of gannets (*Sula bassana*), which were

to be seen simultaneously through a telescope. The bearing and relative range of individual gannets corresponded with the appearance of the radar echoes. At Gibraltar gulls were detected while flying over a sewage discharge at a range of 5,000 yards. An echo of an object approaching Malta was proved to be a migrating stork (*Circonia alba*). It was traced by radar as it flew across the island and out to sea on the other side. Flocks of wild geese (*Anser brachyrhyncos*) were detected approaching East Anglia. Unusual echoes observed after the passage of flying bombs proved to be due to huge flocks of starlings, whose roost was disturbed whenever a flying bomb passed low overhead. The production of echoes from birds has been proved experimentally by hanging a dead gull from a balloon, and detecting it by radar. Though birds gave considerable echoes on 150 centimetre C.H.L. sets for detecting aircraft, they did not provide a serious operational problem, as they could easily be recognized. The echoes given with 10 centimetre ship-watching sets may be much more troublesome. They are detected at about the range where E-boats or motor-launches were picked up, and they often move at similar speeds. The motor-boats are, however, distinguished from birds and aircraft by the rapid increase in signal strength as they approach.

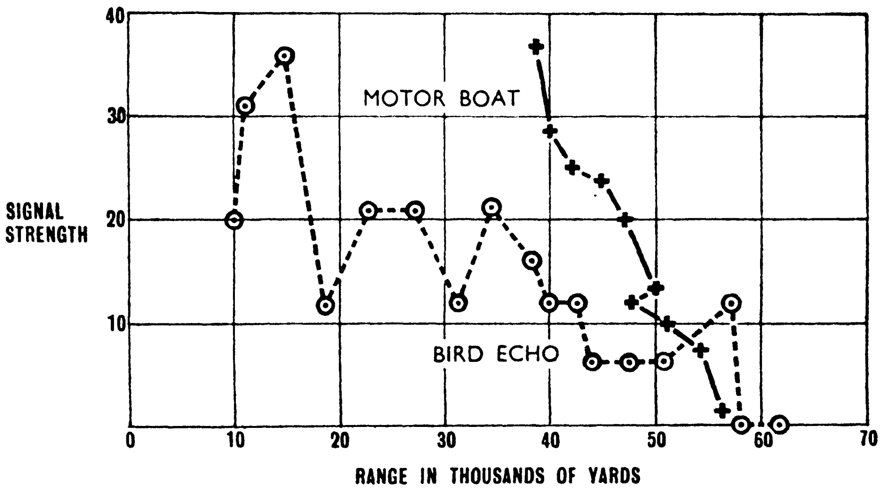


FIG. 39

The plotting of two typical bird and motor-boat tracks is shown in Fig. 39. When both are picked up at 50 to 60 thousand yards, they are not easily distinguishable, but at distances of less than 40 thousand yards the difference in echo strength is very clear.

The Principles of Operational Research

Operational research is concerned with :—

(1) the study of weapons ;
(2) the study of tactics ;
(3) the study of strategy.

The first consists in analysing how and why existing weapons perform as they do, with the object of finding out how they could be improved. The second consists of analysing the various tactical methods in use, with the same object of improving them. The third consists in studying the results achieved by various types of operation, and the cost in the resources of war in achieving them, with aim of suggesting more effective and efficient strategy.

All of these three studies had been pursued in a fragmentary way in the past, but during the war they were brought together and greatly extended, under a military point of view, constituting a branch of warfare virtually new in scope and status. It consisted in the application of scientific method broadly to the whole of warfare. Past operations were studied to determine facts, theories were elaborated to explain the facts, and finally the facts and theories were used to make predictions about future operations.

Warfare is an extremely complicated activity. Its closest parallels are to be found in the realms of biology and economics where a limited amount of numerical data is ascertainable about phenomena of great complexity. Hence the methods used in those sciences are found to be particularly valuable in operational research.

At the beginning of the war, it was thought that biologists would be of little direct value in military work. This proved to be untrue, for they are accustomed to study living organisms, and this involves dealing with many factors at once, when very little may be known about a large number of the individual factors. A special kind of statistics has been evolved for the use of biologists, to assist them in handling problems of this type.

The ordinary way of handling very complicated problems of

which detailed information is very fragmentary is by judgment based on experience. This faculty is developed in the executive man of every type, in the farmer, and in the military commander. After many years of experience, the good military commander acquires skill in judging the value of weapons, tactics and strategy. But he has not the time, or the scientific training, to submit this qualitative judgment to quantitative analysis. It is found that experienced executive judgment in many professions is most likely to go wrong when quantitative analysis requires the application of the theory of probability. The answers to problems of chance, as given by the theory of probability, are frequently in conflict with common sense. One of the obvious examples of this is the continuous prosperity of bookies.

The high commanding officer, with developed judgment, cannot engage in detailed scientific analyses. He needs scientists to assist him.

When the scientist examines an operational scheme, he frequently finds that the commonsense view of it is the correct one. But he backs his view by numerical proof. Thus the commander's decision, which may have been correct from the beginning, is transformed from an emotional judgment into an objective fact. In this way, operational research helps to prevent war being run by gusts of emotion, and hunches.

At the beginning of the war, each of the Services had their own scientific research departments and laboratories, such as the Royal Aircraft Establishment at Farnborough, and the Admiralty Research Laboratory at Teddington. The executive military staffs stated their requirements in new devices and weapons, and these were passed by the Ministry concerned to the appropriate research establishment.

Now the only place where the real operational facts are known is at the military command. Unless the operational requirement is considered scientifically at the command jointly by the military staffs and the scientists, it may not correspond to the real need and to the technical possibilities.

The operational research scientists at the command can help to point out technical possibilities which the military executive would not be scientifically equipped to see ; and they can, as it were, explain the practical facts of life to the technical establishments, who may not be in possession of all the relevant information. For instance, the technical establishments should have access

to signals, track charts, combat reports, meteorological information, etc., which is essential for a full understanding of the technical requirements put to them. Owing to the need for secrecy this necessary access does not always exist and persons are needed to establish it when it is absent.

Hence it was found essential to have operational research scientists working at operational commands, with direct access to the military commanders, and with complete knowledge of all military plans, tactics and strategy. Finally, some of the committees reporting to the Chiefs of Staffs Committee, concerned with the general planning of the war, were attended by scientists in increasing numbers. As one eminent officer is reputed to have said: "Those boys won't even use a soldering iron until they know the whole of the policy of the Pacific War."

This collaboration of military man and scientist gave scope and influence to some of the most outstanding men in the nation, who combined the highest intelligence with the finest scientific training. The first consistent exposition of these principles of operational research was given in a paper on methodology by Blackett.

THE QUANTITATIVE THEORY OF MODERN WARFARE

The permeation of scientific method into wider and wider aspects of warfare has been accompanied by the growth of the conception of a general quantitative theory of warfare, a major military calculus.

For instance, you wish to solve the problem of the destruction of aircraft by gunfire. An aeroplane is a heterogeneous object. It contains engines, a pilot, tanks, etc.; each differentially susceptible to shell fragments of different size and speed. It is to be attacked by a shell whose place of explosion is statistically determinable, and which breaks into fragments travelling in certain directions with certain speeds. How is a shell to be designed so as to do the maximum amount of damage in such conditions? In general, things are more vulnerable when struck from below than from above. The shell should therefore burst below the plane. The damaging effects of shell fragments of various sizes, shapes and speeds on the various parts of the plane can be investigated by fixing up such parts on a firing range and shooting the fragments at them. The first result of this kind of experimental investigation revealed

that fragments of different sizes were needed for the most effective attack on different objects. Hence a shell which broke up into fragments of a definite size was required. Dr. W. Payman solved this problem in one week after it had been put to him at Bernal's suggestion, but the preliminary experiments to find out beforehand what kind of fragments were needed in order to secure particular effects took three years. It is much easier to get what is wanted than to know what is wanted.

Similar principles apply to the attack on a whole country, a town, a division or a ship. All of these are gross objects with component parts which exhibit great variety in resistance to damage. The general problem is how to maximize your efforts with two variables : damaging power and accuracy. The latter goes with numbers, while damage is proportional to the product of number and accuracy. The consideration of this kind of problem leads to the solution of such questions as whether it is worth putting an extra gun on a fighter if it takes five miles per hour off the speed.

All of these problems have their precise inversion. From knowledge of how to protect aircraft against anti-aircraft fire, you learn simultaneously how to make anti-aircraft fire more efficient.

The analysis of operations helps to reveal the time function of the commander. This is often not clear in modern war, because it is so complicated. The commander is hindered in using his judgment adequately because he cannot be expert in all branches of military technique. He needs to have situations analysed, so that those parts which can be reduced to routine can be separated out, while the remaining part, requiring his judgment, can receive the whole of his attention.

The Americans use the word " logistics " to describe the technique of packing stores, and the calculation of how much of every kind will be needed ; the right form of packing, and the order in which the stores are packed. " Logistics " has been a great word in this war. It is derived from the French " *maître du logie*," and has nothing to do with logic. Organization and the mode of tying things together is often more important than improvements in individual weapons. Technical excellence may be wasted by strategical nonsense. For instance, very accurate bombing is no use if you bomb the wrong targets, through failure to choose or find the right ones.

A new instrument may sometimes improve performance by a factor of two, where extra training would improve it by a factor of five. At the beginning of the war, bombing bridges was thought

to be virtually impossible, but in the end it became a decisive factor in the defeat of Germany. This success was gained by training special bridge-bombing squadrons.

The most effective weapon is that which defeats the enemy without killing anyone. One shell may under some circumstances make a whole battalion of men surrender ; in other circumstances, a thousand shells will not. Hence the importance of personnel research : the influence of human and psychological factors on soldiers, of fear and propaganda.

If a high explosive barrage is put up in which $\frac{1}{2}$ lb. of high explosive is dropped per square yard on the deployed enemy's territory, only 2 per cent to 3 per cent of the enemy will be killed, and yet when subsequently attacked they will frequently give up the ground without fighting. If they had not been attacked by the preliminary barrage, they would probably not have been overcome by four times their own number.

Attempts to analyse these effects have been made. For instance, the effects of dive-bombing on troops have been studied. The soldiers were asked what they thought of them. One sergeant-major said " he disliked dive-bombing because it was so accurate," and yet his platoon had been dive-bombed six times without suffering a single casualty. Lethality, or the killing efficiency, was not the intimidating factor.

It must always be remembered that weapons do not fight wars. This is done by men. The amount of strain that men can stand, from every point of view, must be measured.

The same technique of measuring how many shots are needed to shoot down a bomber can also be applied to the estimation of how many shots, from weapons of various kinds and under various circumstances, will be needed to kill a man. Just as bombers are shot at experimentally to find out how many holes are fatal, animals can be shot at and similar information can be deduced as to the average amount of wounds that will be fatal. Some remarkable information has been gained in the study of wounds. It has been shown that if your arm is penetrated by a bullet, it will swell to three times its normal size and contract back again in one-tenth of a second. A bullet can break a bone even if it does not pass within half an inch of it ; and yet it may touch veins and arteries, as it passes through, without damaging them. The fear of wounding has a powerful effect on morale. If the effects of wounding are better understood, the chances of survival are more accurately known, the fear is mitigated.

Air warfare is largely susceptible to calculation. Courage and skill of the individual are the chief human factors involved. Naval

warfare is also susceptible to calculation, though in a lesser degree. But land warfare involves additional human factors. There are the complexities of terrain, and the mass-psychology of large numbers of troops. Hence judgment and capacity to command are specially important in land warfare. The situation is too complicated to be susceptible of much calculation, but the commander must appear to be master of the situation. It is very necessary for mass psychological reasons to give at any rate the impression of controlling things. The air commander is much less involved with these factors. He can approach his problem with more objective, calculating detachment and a less emotional attitude.

The modern technique of warfare shows tendencies towards graded sets of developments following a definite order. In primitive shooting, you aim at an object you can see directly. The next stage is firing at an image in an instrument. The next stage in evolution is the proximity weapon, torpedoes and bombs that follow or " home " on to their targets. These need not be very powerfully armed, for they follow the target about and are nearly certain to achieve direct hits.

This tends to reduce war to a completely automatized and mechanized activity. The final aim is the completely automatic war—using generalized radio. The whole spectrum of electromagnetic waves will be utilized in the various wavelengths for the appropriate purposes—radio-waves, heat radiation, visible light, ultra-violet waves, X-rays.

This is the major conception—the reduction of war to a rational process. It is the contrary of that held by Hitler, who had a romantic view of war. He believed that wars are to be won by great strokes of inspiration. He was always out for the new and the romantic. Systematic scientific work on known weapons paid larger and quicker dividends. It beat Hitler. The romantic conception of war is becoming out of date. It is not consonant with the systematic, rational, scientific kind of warfare which is evolving from the inter-penetration of war and science. It is incompatible with the exercise of mystic qualities of leadership and initiative. Hitler was advised by Speer, no doubt a very competent technical man, but Speer did not have the initiative. Hitler and his generals failed to produce any operational research comparable to the British development. If they had, they would probably have won the submarine campaign and the war. But it was impossible for them to collaborate on a basis of equality with the rational, equalitarian scientists, who, when they enter into the conduct of warfare as a whole, look at it in a civilian spirit. For the traditional romanticism of war is the contrary of the civilian scientific spirit,

and it is therefore natural that when the scientist begins to join in the conduct of war, he enters into it as a civilian. That is why the directors of operational research are generally civilians, and one reason why war in the future will tend more and more to be conducted in a civilian spirit. One reason why Hitler failed is that he was out-of-date.

III.

THE ATOMIC BOMB

RUTHERFORD

The introduction of the atomic bomb was the greatest event of the war, though not the most decisive. The outcome of the war had been decided before it was introduced. The development of radar and other inventions, together with the Allied superiority in numbers and economic resources had made the defeat of Germany and Japan certain. But the use of the bomb against Japan greatly shortened the Far Eastern part of the war, and saved the lives of a host of Allied soldiers, and the further destruction of vast quantities of material and man-made goods.

The genius that presides over the achievement of the release of atomic energy is the late Lord Rutherford's. He, and his colleague Professor F. Soddy, introduced the theory of spontaneous disintegration which, in 1902, gave the first adequate explanation of the phenomena of radioactivity discovered by Becquerel in 1896. He propounded in 1911 the nuclear theory of the atom, which was the intellectual guide that showed the way to the release of atomic energy. He instantly recognized the marvellous value of Professor Niels Bohr's quantum theory of the atomic mechanisms, and gave him complete support and encouragement, and a place on his staff. He was the first to transmute atoms, and thus begin to bring the release of atomic energy under human direction and control. He taught his pupil, now Sir James Chadwick, who subsequently discovered the neutron and became the chief British participant in the invention of the atomic bomb. Professor Otto Hahn, who discovered the fission process in uranium, the immediate starting-point for the atomic bomb development, was one of Rutherford's pupils. Cockcroft, who, with Dr. E. T. S. Walton, first disintegrated atoms by electrical machinery and thus brought atomic energy within sight of utilization, made his classical experiment in Rutherford's laboratory. Many of the other eminent scientists who have contributed to the development of the atomic bomb were his personal pupils and all have been his intellectual pupils.

The modern knowledge of the atom is the result of the co-operation of many research workers of many nations, in the manner which is characteristic of modern scientific activity. The British have made their contributions, and the greatest of these was the production of Rutherford himself. What was this great man like? He was born in New Zealand, the son of a farmer of Scottish descent, and a woman school teacher, said to be the first in that country. Throughout his life, he had the energetic, open way of a pioneer farmer. He was physically big, and he seemed to carry the fresh air with him. His hair and moustache were shaggy and his complexion was weathered. He had a noble way of holding back his head, and at times his eyes flashed, and he bared his teeth. These looks of a modern viking suddenly changed when he put his glasses on, and became studious. The son of the village schoolmistress then appeared.

He had a simple zest for life which was not characteristic of the educated English among whom he settled. He never quite acquired their accent, and he had a natural enthusiasm they loved but were too inhibited to share fully. His interest in persons and their problems, with his powerful memory and sympathetic intelligence, attracted a widespread affection. Behind his heroic exterior, which expressed one side of his genius so well, there was a very sensitive highly-strung intelligence, which operated more by subconscious intellectual feeling than by conscious logic.

Niels Bohr once said, " Rutherford is not a clever man ; he is a great man." He was often ill-at-ease with very clever people. He did not like arguing with men who produced networks of ingenious arguments that contained no obvious flaws, but which he felt to be wrong. He adopted a magisterial attitude to such people, which was in some degree a mechanism for defending his sensitive and modest inner intelligence.

Rutherford arose out of the British pioneering civilization, combined with an education in the English scientific tradition and his own great inherent ability. His gifts were unfolded by the fresh air of New Zealand, the subtle scientific inheritance from Newton and Faraday, and the spirit of freedom seen in the best side of British history.

RADIOACTIVITY

One of the first observations made on radioactivity after it was discovered in 1896 was that it seemed to be an inexhaustible source of light and heat. These were emitted without any detectable change or diminution with time.

This mode of production of light and heat was quite different from that produced in the burning of oil, or other fuel, which is accompanied by complete chemical changes. The oil combines with the oxygen of the air and forms carbon dioxide, water vapour and other products, and, as oil, disappears. The amount of energy produced in burning oil is relatively small compared with the extraordinary changes that combustion brings.

In contrast, radioactivity produced quantities of energy which appeared to be unlimited, without the accompaniment of any obvious change. All kinds of speculations were offered to explain where the energy came from. One theory was that the radioactive substances were able to capture energy wandering in space, and re-emit it. In that way the apparently unlimited supply could be explained.

Further studies soon showed, however, that radioactive substances change intensely, though not in the same way as in burning or chemical action. They were found to produce substances that were not there before. They emitted radiations like X-rays, and others like cathode rays. Three kinds of radiations were sorted out and called the α, β and γ rays. Rutherford showed that the α rays were really atoms of helium. The β rays consist of electrons, and the γ rays of very short electromagnetic waves. The discovery that the α rays were atoms of helium was very important because it indicated that one kind of elementary atom was giving birth to another ; that uranium was producing helium from within itself. Matter of one kind was spontaneously changing into another kind : a natural transmutation of matter was taking place.

It was evident that the radioactive atoms were exploding, and that the enormous store of energy released in radioactivity was coming from within the atoms. Evidently, prodigious stores of energy were locked up somehow within the atoms. Matter, such as stone, water, iron, consists of atoms. How could such cold and inert things contain prodigies of energy ? Centuries of science had established the conception of atoms as the ultimate, immutable constituents of matter. How impossible suddenly to conceive them as packets of the most intense and violent energy !

Very swift and brilliant analysis of the phenomena led Rutherford and Soddy to announce in 1902, only six years after the original discovery of radioactivity, their theory of the spontaneous disintegration of atoms. They asserted that atoms, the very foundation of matter and nature, were exploding, and not according to any rule, but merely by chance. Einstein has said that he " could not believe that the Almighty had organized the world according to the throwing of dice." It needed a bold spirit to adopt chance

as the first principle in the explanation of the transmutation of the fundamental atoms of matter.

Perhaps Rutherford's Calvinist up-bringing, of which he was proud, disposed him towards the adoption of chance in the explanation of nature, for the Calvinist regards salvation as due purely to the chance intervention of Providence, and not as a reward for the observation of law and goodness. Rutherford dealt with classical physical conceptions with a grim ruthlessness worthy of his co-religionists. Sir Arthur Eddington once said that Rutherford's conception of spontaneous atomic change was the most revolutionary of all the brilliant flights of the modern scientific imagination.

The new theory brought order into the extremely complicated and mixed series of radioactive changes. The three radiations emitted by radioactive substances were coming from inside the atom. Why not interrogate these messengers, and learn what their native place was like : how it was shaped and inhabited ; and by what mechanisms and laws it was ruled ? Why not force the rays to reveal the inmost secrets of the atom, the clue to its transmutation, and the key to the release of its stores of energy ?

Rutherford forthwith bent his full genius to the task. Within nine years he had made the rays reveal the general structure of the atom. He proved that atoms are not little hard balls, but very spacious structures, consisting of a few distant electrons circulating round a relatively heavy nucleus, like the planets round the sun of a miniature solar system. Nearly all the mass of the atom was concentrated in the nucleus, which carried a positive electric charge exactly balancing the sum of the negative electric charges carried by the circulating electrons.

The new conception of the atom at once explained many things. It was evident that the superficial changes that occur in chemistry, burning, etc., are concerned with the electrons in the outside of the atom. That which remains unchanged in chemical action, that passes through one combination after another in the formation of compounds, is the nuclei of the atoms of iron, oxygen, etc. In radioactivity, the changes are utterly different. They are due to the spontaneous disintegration and change of the nucleus itself.

While these tremendous advances in the experimental knowledge of matter were being made, very great advances in scientific theory were being elaborated. Max Planck had propounded in 1900 the theory that energy is not emitted in a continuous flow, but always in a collection of packets of finite size. He was driven to accept this view in order to explain the distribution of the energy found

in the light from hot bodies such as the sun. His conception struck at the principle of continuity as the comprehensive basis of nature.

The equally brilliant theory of relativity was proposed by Einstein in 1905 to explain the observed fact that the speed of light is constant under all conditions. The theory of relativity was extended to all the motions of nature, and it began to be evident that many apparently different things were the same fundamental thing seen from different points of view. Space and time, which according to the old ideas seemed utterly different, were in the light of relativity seen to be two different aspects of one underlying unity.

From this line of development, Einstein showed that mass and energy were one of these pairs of interchangeable aspects. Mass could be conceived as congealed energy ; and he even calculated how much energy there would be in a unit of mass. He found that it would be enormous. When energy was released, mass disappeared. The annihilation of mass would be accompanied by a vast and proportionate output of energy. If a mass of one ounce of matter could be transformed into energy, it would produce enough to turn nearly one million tons of water into steam.

In fact, however, only a small fraction of the mass is transformed into energy when an atom explodes. This energy comes, not from the annihilation of the constituent particles of the atom, but from the release of the " binding " energy that holds them together.

It is certain that even the slightest emission of energy is accompanied by a loss in mass. When the fire burns in the grate, the mass of the products of combustion is slightly less than the mass of the original materials taking part in the burning. But the loss is too small to be detected by any known balance or direct method of weighing.

The enormous stores of energy released by the annihilation of mass provided astronomers with the clue to the origin of the almost perpetual shining of the sun and stars. Quite recently, an explanation of how the sun generates its own rays has been given by Bethe. He has succeeded in giving a quantitative as well as qualitative account of the sun's shining. He has deduced the magnitude of the sun's output of energy from modern atomic principles, and its age. The first result agrees with the direct measurement of the strength of the sun's rays, and the second with the facts of solar astronomy, geology, and the time needed for the processes of biological evolution.

In 1914, however, while the magnitude of the stores of atomic energy had been discovered, and examples of its release in radioactive substances directly observed, no method of influencing its

as the first principle in the explanation of the transmutation of the fundamental atoms of matter.

Perhaps Rutherford's Calvinist up-bringing, of which he was proud, disposed him towards the adoption of chance in the explanation of nature, for the Calvinist regards salvation as due purely to the chance intervention of Providence, and not as a reward for the observation of law and goodness. Rutherford dealt with classical physical conceptions with a grim ruthlessness worthy of his co-religionists. Sir Arthur Eddington once said that Rutherford's conception of spontaneous atomic change was the most revolutionary of all the brilliant flights of the modern scientific imagination.

The new theory brought order into the extremely complicated and mixed series of radioactive changes. The three radiations emitted by radioactive substances were coming from inside the atom. Why not interrogate these messengers, and learn what their native place was like : how it was shaped and inhabited ; and by what mechanisms and laws it was ruled ? Why not force the rays to reveal the inmost secrets of the atom, the clue to its transmutation, and the key to the release of its stores of energy ?

Rutherford forthwith bent his full genius to the task. Within nine years he had made the rays reveal the general structure of the atom. He proved that atoms are not little hard balls, but very spacious structures, consisting of a few distant electrons circulating round a relatively heavy nucleus, like the planets round the sun of a miniature solar system. Nearly all the mass of the atom was concentrated in the nucleus, which carried a positive electric charge exactly balancing the sum of the negative electric charges carried by the circulating electrons.

The new conception of the atom at once explained many things. It was evident that the superficial changes that occur in chemistry, burning, etc., are concerned with the electrons in the outside of the atom. That which remains unchanged in chemical action, that passes through one combination after another in the formation of compounds, is the nuclei of the atoms of iron, oxygen, etc. In radioactivity, the changes are utterly different. They are due to the spontaneous disintegration and change of the nucleus itself.

While these tremendous advances in the experimental knowledge of matter were being made, very great advances in scientific theory were being elaborated. Max Planck had propounded in 1900 the theory that energy is not emitted in a continuous flow, but always in a collection of packets of finite size. He was driven to accept this view in order to explain the distribution of the energy found

in the light from hot bodies such as the sun. His conception struck at the principle of continuity as the comprehensive basis of nature.

The equally brilliant theory of relativity was proposed by Einstein in 1905 to explain the observed fact that the speed of light is constant under all conditions. The theory of relativity was extended to all the motions of nature, and it began to be evident that many apparently different things were the same fundamental thing seen from different points of view. Space and time, which according to the old ideas seemed utterly different, were in the light of relativity seen to be two different aspects of one underlying unity.

From this line of development, Einstein showed that mass and energy were one of these pairs of interchangeable aspects. Mass could be conceived as congealed energy ; and he even calculated how much energy there would be in a unit of mass. He found that it would be enormous. When energy was released, mass disappeared. The annihilation of mass would be accompanied by a vast and proportionate output of energy. If a mass of one ounce of matter could be transformed into energy, it would produce enough to turn nearly one million tons of water into steam.

In fact, however, only a small fraction of the mass is transformed into energy when an atom explodes. This energy comes, not from the annihilation of the constituent particles of the atom, but from the release of the " binding " energy that holds them together.

It is certain that even the slightest emission of energy is accompanied by a loss in mass. When the fire burns in the grate, the mass of the products of combustion is slightly less than the mass of the original materials taking part in the burning. But the loss is too small to be detected by any known balance or direct method of weighing.

The enormous stores of energy released by the annihilation of mass provided astronomers with the clue to the origin of the almost perpetual shining of the sun and stars. Quite recently, an explanation of how the sun generates its own rays has been given by Bethe. He has succeeded in giving a quantitative as well as qualitative account of the sun's shining. He has deduced the magnitude of the sun's output of energy from modern atomic principles, and its age. The first result agrees with the direct measurement of the strength of the sun's rays, and the second with the facts of solar astronomy, geology, and the time needed for the processes of biological evolution.

In 1914, however, while the magnitude of the stores of atomic energy had been discovered, and examples of its release in radioactive substances directly observed, no method of influencing its

release had yet been discovered. Rutherford set about using the new insight into the structure and mechanism of the atom to try to change one kind of atom into another. If nature performed this spontaneously in the transformations of radioactive substances, could not man discover some way of producing such transformations artificially?

Evidently, an instrument of an enormous and new degree of intensity would be needed to effect changes in the nuclei of atoms. None of the methods familiar to chemistry and physics would be intense enough. The only known source of such intensity was natural radioactivity. Could the enormous energy of natural radioactivity be harnessed to produce an artificial transmutation of atoms?

When certain radioactive atoms explode, they release some of their energy by communicating it to the atomic fragments flung out in the explosion. As has been mentioned, some of these fragments consist of nuclei of atoms of helium. They are flung out with immense speed and hence high energy of movement. Why not direct these against the citadel of an atom, against its nucleus? Rutherford was preoccupied with this idea when the war of 1914 began. He was called by the British Government to assist in the scientific struggle against the German submarines and was very busy with this work. But he kept the attacks on the atom going. While the Germans were shelling Verdun, Rutherford was bombarding the nucleus in his laboratory at Manchester, when he could find the time.

In 1918 he failed to appear at the meeting of an important war science committee. When one of his colleagues asked him why he had failed to appear, he said that he had just got definite evidence that it might be possible to disintegrate an atom at will, and that if this proved to be true " it was far more important than the war."

Immediately after the conclusion of the war, while still in Manchester, he completed this investigation and in 1919 published a conclusive proof that atoms of nitrogen could be transmuted by bombardment with atomic projectiles from natural radioactive substances; and later, in Cambridge, he extended his investigations to the study of the artificial disintegration of the atoms of many light elements. He was assisted in this especially by Chadwick, who had been one of his most brilliant pupils and collaborators at Manchester.

Chadwick went to study in Berlin just before the beginning of the first world war. As soon as this broke out he was interned by the Germans in the camp at Ruheleben, where he spent the remainder

of the war. He was joined there by Dr. C. D. (now Sir Charles) Ellis, until recently Scientific Adviser to the Army Council, a regular army officer cadet who had also been caught in Germany by the outbreak of war. Ellis extended his scientific interests during his internment. When the war ended, Chadwick joined Rutherford in Cambridge ; Ellis abandoned his army career and also went to Cambridge, to continue his study of physics.

The success of these scientists in rising to the achievement of a long series of important discoveries after four years of imprisonment is a remarkable demonstration of intellectual determination and scientific passion. Rutherford and Chadwick and their colleagues succeeded in transmuting atoms of many light elements in the early years after 1919, but it was evident that new methods of producing atomic projectiles were required. The atomic guns provided by radium were too weak, cumbersome and crude. Some weapon, more violent or more subtle, and under control, was required. In that wonderful year of 1932, both of these were discovered, within six weeks of each other, in Rutherford's laboratory.

Some years before, the German physicists Bothe and Becker had discovered some very penetrating radiations obtained by bombarding the light metal beryllium with particles shot out of polonium. They assumed that the radiations were of a wave nature. The French physicists Frederic Joliot and his wife Irene Curie—whose mother Marie Curie had discovered polonium and named it after her native country—studied these radiations and made a very striking experiment. They found that if a piece of paraffin wax was placed in front of them, then the amount of radiation seemed to be increased, and not decreased by the interposition of the wax. Chadwick, by further experiment and interpretation, was able to prove that this paradox could be resolved if the radiations were not waves, but a new kind of atomic particle without any electric charge. Thus he discovered the neutron.

Rutherford had forecast in 1920 the existence and some of the qualities of such a particle. He had explained that such a neutral particle would have particular ease in penetrating atoms and matter, because, having no electric charge, it would not be repelled by other electrically charged particles, such as the nuclei of atoms.

The atomic projectiles shot out of radium and used in the first disintegration experiments consisted of nuclei of atoms of helium. It has been explained that such nuclei have a positive electric charge. Now the size of this charge is connected with the size of the nucleus. The nucleus of a heavy atom has a large electric charge. This repels very strongly any charged particle shot at it. This explains why

Rutherford's first technique was successful with light atoms such as those of nitrogen and lithium, but it would not work with those of iron, gold, and others of very immediate practical interest. The neutron, however, was free to stroll into even the heaviest of the charged atomic nuclei. Thus subtlety and guile stole a march on violence and circumvented the charged barriers of the nucleus.

But violence caught up very rapidly. Rutherford had told his young men that he wanted " a million volts in a soap box "—some powerful, compact electrical machine that could be used for flinging artificially accelerated atomic projectiles at all kinds of atomic nuclei. T. E. Allibone constructed powerful electrical accelerators. Then the theoretical researches of Gamow, and Gurney and Condon, showed that the penetration of atomic nuclei should be much easier than had previously been thought. This led Cockcroft and Walton, an Irish physicist who had made an important review of methods of accelerating particles, to concentrate on producing streams of swift protons. Cockcroft was an electrical engineer from Manchester. He had graduated as an engineer at the Manchester College of Technology and joined the engineering firm of Metropolitan-Vickers Electrical Company, Ltd. After spending four years in the Army in the war of 1914-1918 he returned to his firm. He engaged in advanced study with Professor Miles Walker and was presently awarded a post-graduate scholarship to continue his studies at Cambridge. His engineering knowledge fitted him to devise powerful electrical apparatus, and he attacked the problem of devising an electrical machine by which an electrical field of several hundred thousand volts could be applied to atomic particles, so that they could be given a very high speed and energy, like those thrown out naturally by radium. Cockcroft and his colleague Walton succeeded in disintegrating lithium with electrically accelerated protons in 1932, shortly after Chadwick's discovery of the neutron. This was a great advance, because electrical machines could be developed, and large streams of atomic projectiles could be produced at will.

Cockcroft used protons, the nuclei of hydrogen atoms, in his first experiments. Each proton released about sixty times as much energy as it possessed itself. But the number of protons accelerated was relatively insignificant, and the amount of energy used in producing the accelerating field was much greater than the total amount released in the atomic disintegrations. As a machine, Cockcroft's atom-smasher was very inefficient in the engineer's sense. Each release of atomic energy required a separate bombarding proton, and only one proton out of every million had enough energy

left, after collisions, to disintegrate an atom. As soon as the proton-stream was stopped, the disintegrations stopped. Could a process of atom-burning be found, like coal-burning, in which the fire spreads from one igniting match ? Could one proton be used as a match for disintegrating one atom, whose fragments would in turn disintegrate the adjacent atoms, and so on, until the whole mass of atoms became one explosion of atomic energy ? This seemed a remote prospect in 1932.

Atomic physics nevertheless continued to advance at a tremendous rate. Professor E. O. Lawrence devised his marvellous cyclotron, which whirls atoms round, like stones on the end of a piece of string, until they have acquired enormous speeds. Anderson discovered the positive electron in cosmic rays. Then Joliot and Curie discovered that many ordinary atoms could be made artificially radioactive by bombarding them with atomic projectiles. This was of very great importance, for it showed that science need not be limited to the use of the rare naturally radioactive substances found in the earth. Man might be able to manufacture unlimited quantities for his own use.

Then, in 1934, Professor Enrico Fermi in Rome poured out a bewildering series of discoveries by systematically bombarding atoms of all the elements with neutrons. He found that several dozen of them could be transmuted by neutrons, and he obtained particularly interesting results from uranium. This is the most complicated of the ninety-two different kinds of chemical atoms found on the earth. These can be placed in an order of complication, depending on the number of electric charges on the nucleus. The first in the series is hydrogen, with one positive charge, and therefore known as Atom No. 1, and the last is uranium, with ninety-two charges, and therefore known as Atom No. 92. It is not surprising that Atom No. 92 should be naturally radioactive. It might well be too complicated to be stable. It is in fact an ancestor of radium, whose atomic number is 88.

Fermi found that the bombarded uranium produced numerous atoms with chemical properties quite different from uranium. He concluded that he had made new atoms, more complicated than uranium atoms, and supposed that these must be " trans-uranian " atoms, Nos. 93, 94, etc. He seemed to have made a new series of atoms hitherto not found on the earth.

AGGRESSION BEGINS

Such, in very brief outline, was the position of research in nuclear physics in 1934.

By that date, profound changes had occurred in Europe. In 1933 the Nazis secured complete power in Germany, and began to use it for the realization of their social and political aims. They launched the most formidable armaments programme which, up to that time, had ever been attempted. Among their aims were the extermination of the Jews and the domination of the world by themselves, as the self-styled " master-race," which, they believed, contained some quality which made them superior to other men in the realm of leadership. Two of the results that followed from these ideas and actions were that many leading Jewish scientists left Germany, and that the Nazi leaders never succeeded in dealing with science and scientists satisfactorily. Being convinced that they had a gift and an intuition superior to scientific knowledge, they never learned to co-operate even with scientists who claimed to be Nazis.

The German Jewish scientists who came to England under the persecution included Dr. Rudolph Peierls, a young research physicist of Berlin ; and Dr. Franz Simon, professor of physics in the University of Breslau. Peierls was presently appointed professor of applied mathematics in Birmingham, and Simon, reader in thermodynamics at Oxford.

As the Nazis obtained more and more influence over Italy, they intensified persecution in that country. More specific persecution of the Jews was added to the violence already practised by Mussolini. When Fermi left Italy in 1938, in order to receive at Stockholm a Nobel prize for the remarkable discoveries that have been mentioned, he did not return to his native land. He accepted a chair in Columbia University, New York, and settled in America.

Dr. Lise Meitner, the life-long scientific collaborator of Hahn of Berlin, the leading authority on the chemistry of the radioactive elements, left her native land, and settled first in Copenhagen and then in Stockholm. Dr. O. R. Frisch, a brilliant young Austrian physicist who had been working at Hamburg, came to England, then went to work in Bohr's laboratory at Copenhagen, and then came back to England, first to Birmingham, where he worked on fission before the war began. Then he joined Chadwick at Liverpool, late in 1940, when the resources of Birmingham, had been overwhelmed in developing radar. The young Austrian experimental physicist Dr. H. Halban joined Joliot in Paris, and became a French citizen.

A new Exodus occurred, this time not only to other countries, but into new regions of knowledge of nature, into new insight and mastery of the world within the atom.

It has been mentioned that Fermi had shown that neutrons transmute uranium into a number of atoms with very different chemical properties. Hahn and Meitner were masters of radio-chemistry who might be expected to unravel the chemistry of the confusion of transmuted uranium atoms. They were dealing with excessively minute quantities of the new substances, which they accepted at first as " trans-uranian " atoms, Nos. 93, 94, etc. But as they secured more and more chemical knowledge of the new substances, the confusion grew worse, and not better.

Late in 1938, Hahn and Dr. F. Strassmann, in reviewing the chemical knowledge of the new substances, recognised that one of them was probably barium, whose atomic mass and number are only about half of that of uranium. This meant that they had previously been on a false trail. Frisch and Meitner, now in Scandinavia, immediately explained the significance of this discovery. Neutrons did not transmute uranium atoms into new atoms slightly heavier or more complicated, with a higher atomic number. They split these big uranium atoms into two roughly equal parts. The splitting could be done in a variety of ways. Uranium atom No. 92 might be split into Barium No. 56 + Krypton No. 36 ; or into Strontium No. 38 + Xenon No. 54. Dr. J. R. Dunning in America rapidly repeated the work on fission.

Here was the explanation of the chemical confusion : a wide variety of chemically different atoms was being produced by the disintegration. Frisch and Meitner named this new process of atom-splitting " nuclear fission." Nothing like this had been seen in heavy atoms before.

They also pointed out that as the sum of the masses of atoms of barium and krypton is considerably less than the mass of the uranium atom, the two parts resulting from the fission would fly apart with very great energy. The loss of mass indicated that this energy must amount to about 200,000,000 electron volts per single fissured atom. Frisch in Copenhagen and Joliot in Paris independently proved these facts experimentally. This output of energy was more than ten times as much as had been obtained in the disintegration of atoms such as lithium. When an atom of carbon combines with oxygen in the burning process in a fire, about 4 electron-volts of energy are released. Thus the scale of the production of energy by uranium fission is fifty million times greater. A coal fire only gives a considerable amount of energy because every carbon atom of the enormous number of millions in it gives up its quota of 4 electron-volts, derived from the rearrangement of the electrons in its outer spaces, and in no degree whatever from its

nucleus. But a coal fire in which vast numbers of atoms each give a little energy may provide a larger total of energy than a uranium disintegration in which a very few atoms individually give a great deal. How could a large number of uranium atoms be made to fissure in very close succession, so that a large total emission of energy could be secured at any moment?

The question just posed brings out the essential difference between the use of fire energy and the use of nuclear energy. Man, in the early days of his evolution, made an enormous stride forward when he used Nature's gift of fire. He did not know how fire worked, but used it quite happily and successfully for hundreds of centuries before properly understanding it. He was familiar with the volcano, lightning, meteors and forest fires. The mysterious flame was sometimes worshipped in his religious rites. The Virgins of the Temples of Vesta and the human fire-carriers of the native Australians and Tasmanians are examples. Nature in the early days of the human race was lavish with her gifts of fuel. The wood of the forest, the coal in outcrop, surface oil seepage, were all signposts to rich and readily available stores. How different with atomic energy! The understanding of many of Nature's hidden mysteries had to come first, before her jealously guarded secrets of the, perhaps last, hoards of natural terrestial energy could be tapped. The atomic bomb, that is, the new source of energy of which it is the terrible sign, is the greatest wonder and achievement of this or any other age, stupendous in its achievement and its implications for good and evil.

Bohr, the acknowledged leader of theoretical atomic physics, had been in the closest touch with the experiments of Frisch and Meitner, which were made in his own institute. He had for several years led a search for some general conceptions to summarize the very large and varied facts that had been collected on the phenomena of nuclear disintegration, and in October 1939, with the collaboration of Professor J. A. Wheeler of New York, he published a comprehensive account of his theory.

From one point of view, nuclei appeared to consist of very closely packed sets of individual particles, making a kind of matter of enormous density of the order of a thousand million times that of water. How could such closely packed particles keep any individuality? About half of them would be positively charged and ought to repel each other. There must be new forces at work, overcoming these repulsions and holding all the particles together.

The nucleus is probably more like a drop of fluid. Pursuing this idea, Bohr has successfully explained many of the observed facts of

fission, and has also made striking forecasts of new examples of fission phenomena, which have since been confirmed by experiment. If you try to distort a spherical liquid drop, your disturbing force will be opposed by the surface tension on the drop. The surface tension will act in opposition to a change in the shape of the drop. The short-range forces which hold together the mutually repelling particles in the spherical nucleus may be compared with the surface tension in the liquid drop.

The excitation energy of a nucleus, on the analogy of the distorting force on the drop, must be expected to give rise to modes of motion of the nuclear matter similar to the oscillations of a fluid sphere under the influence of surface tension. For heavy nuclei, however, the high nuclear charge produces an effect which to a large extent counteracts the restoring force due to the short-range attractions responsible for the surface tension of nuclear matter.

The behaviour of a nucleus under deforming forces may therefore be compared with that of a drop of liquid under analogous forces.

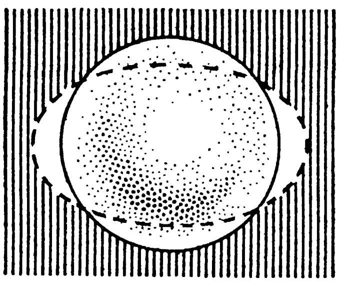


FIG. 40

The continuous line in Fig. 40 represents a spherical liquid drop which has a uniform electric charge, corresponding to the electric charge on the nucleus of an atom. Small deformations of the liquid drop, from the spherical form (represented by the dotted line) lead to characteristic oscillations about the spherical shape. The drop vibrates in and out. If the electric charge on the drop is raised to a certain critical value, the spherical form becomes unstable even for very slight deformations. This critical value is the square root of ten times the product of the surface tension and the volume of the drop. If the electric charge is slightly smaller, the drop will have to be considerably deformed before it becomes unstable, as in Fig. 41. As the charge is reduced further, the deformation leading to division will require to be of the degree

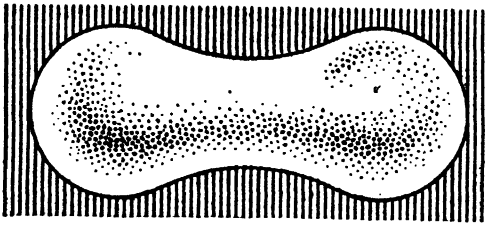


FIG. 41

shown in Fig. 42, and at a still lower charge, the deformation must reach the degree of two small spheres just in contact.

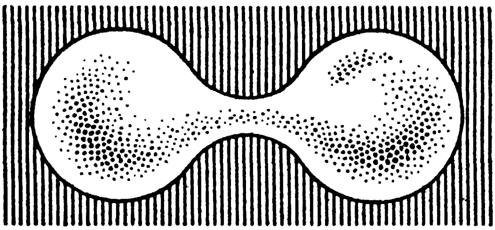


FIG. 42

Bohr now calculated by analogy what force would be necessary to divide an atomic nucleus into two parts, supposing that it behaved like an electrically charged drop made to divide into two droplets. He found a simple formula for its dependence on the size of the electric charge on the nucleus (which is given by the atomic number) and the mass of the nucleus. With this he accounted for the facts of uranium fission which had been observed. He explained that the three different kinds, or isotopes, of uranium atoms would behave differently, according to their differences in mass, and that most of the fissions observed were probably due to the rare isotope Uranium 235. He explained why thorium and uranium behaved so differently with regard to fission, and he forecast that the fission possibilities of protactinium would be worth investigating. In this beautiful work, so typical of his genius, Bohr was drawing upon the thought and knowledge of his first researches as a young man. These were on the properties of fluid jets and droplets.

The Bohr-Wheeler theory forecasts the general features of the fission properties of all atoms, known or unknown. It was possible

to forecast that if a trans-uranian element of atomic number 94 could exist, it would exhibit the property of easy fission. Since Fermi's original experiments, it has been definitely proved that bombarding neutrons of a certain energy can be absorbed into the uranium nucleus 238. This presently emits an electron which thus increases the positive electric charge on the nucleus to 93 units and thus forms a new atom, No. 93. This element, not found naturally on the earth, has been given the name neptunium. The atom of neptunium then emits a second electron, which causes the nucleus of No. 93 to be transmuted into yet another new atom, with charge 94 units. This atom, named plutonium, is also not found naturally on the earth. It follows from the Bohr-Wheeler theory that plutonium should be susceptible of easy fission.

The forecast of the fission-properties of plutonium, with the subsequent discovery of the element and proof of these properties, is of particular interest, as it shows that science is no longer restricted to the supplies of easily-fissured atoms found existing naturally in the earth. It is possible to convert by pre-treatment an atom which does not easily fissure, into one that easily fissures. Hence a step has been made towards converting matter that does not easily provide atomic energy into matter that may.

Very soon after the discovery of uranium fission by Hahn and Strassmann, Joliot and his colleagues Halban and Dr. L. Kowarski made a fresh discovery of fundamental importance. This indicated that when the atom of uranium splits in two, several neutrons are released at the same time. They estimated that there were three or four of them. In America, at about the same time, Dr. H. L. Anderson, Fermi, Dr. H. B. Hanstein, Dr. L. Szilard and Dr. W. H. Zinn independently showed that more than one neutron was released in each uranium fission. It was immediately evident that if each exploding uranium nucleus produced four neutrons, then each of these four neutrons might cause four more neighbouring uranium atoms to explode, releasing sixteen more neutrons, leading to the explosion of sixteen more uranium atoms, and so on. Thus a vast number of uranium atoms might be fissured almost simultaneously, leading to the release of energy at a prodigious rate.

In the excitement of pursuing the implications of Joliot's experiment, you may not have paused to consider where the four neutrons might have come from. But if you did, you will have found that Bohr already had the answer. He recalled Plateau's demonstration that when a liquid sphere splits into two droplet-halves, there is a tendency for a number of minute droplets to form in the region of separation between the two halves. Those neutrons might be

compared to these minute droplets. The two drops are "hot" or in a state of vibration, and the neutrons come out as a result of "evaporation."

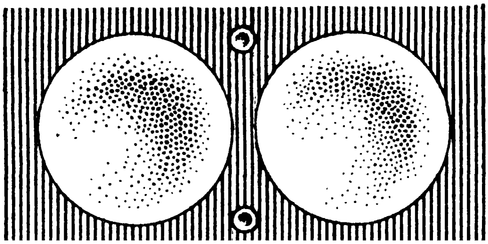


FIG. 43

Thus, under suitable conditions, it appeared conceivable that one neutron might theoretically act as a trigger to cause a whole volume of uranium to disintegrate, with prodigious output of energy.

The release of atomic energy on a practical scale was now in sight. The scientists had two major problems. The first was to discover how this chain of atomic disintegrations might be started, and the second was how it might be brought under control. The first would provide something in the nature of a super-bomb, the second would be necessary in order to utilize atomic energy for civil purposes, for an explosive is only of limited value to industry. Atomic energy would not be of direct use to mankind in home and factory unless it were under complete control.

So, early in 1939, a race had begun into the discovery of how to release atomic energy.

Then Germany declared war.

WAR BREAKS OUT

Joliot's experiments showed that most of the neutrons released in a uranium fission were travelling fast. Now the slow neutrons were found to produce fission more easily. Hence attempts were made to slow down the fast neutrons by mixing uranium with substances which behave like elastic buffers to neutrons, such as "heavy water" (the special kind of water containing hydrogen atoms of double the usual mass), helium, beryllium and carbon.

Research on these lines was pursued by Fermi in America, Professor G. P. Thomson in England, and others ; in addition to the group of French workers. They were aiming especially at the release of atomic energy under controlled conditions, which is of far greater value for scientific research purposes and civil applications than an explosive release.

If the chain of atomic disintegration is to be propagated by very slow neutrons, it looks on general grounds as if the reaction will not proceed very quickly, for it must depend on the speed with which the neutrons move through the mass of uranium.

The outbreak of war had increased the interest in the possibility of producing an atomic bomb for military purposes. Frisch and Peierls at Birmingham, and Chadwick at Liverpool independently pointed out that atomic energy released by slow neutrons would not produce an explosive much more violent than T.N.T., and the known kinds of chemical explosive. A catastrophic chain of atomic fissions would require the utilization of fast neutrons.

The production of such a chain in ordinary uranium consisting mainly of atoms of Uranium 238 seemed unlikely. The atoms of Uranium 235, which are specially susceptible to fission, would be in very dilute distribution through the uranium mass. Hence the chain of reactions would grow slowly in such a mass, and this would have to be very large, if the chain were to work up to any considerable speed.

If you have a small block of uranium, many of the neutrons generated in its interior will escape through the surface into the outer air before they have had a chance of fissuring a suitable uranium atom. The larger the block, the less likely is this to happen, for the production of neutrons is spread through the volume of material, and therefore the number depends on the volume, while their chance of escape, without causing any disintegration, depends on the area of the surface. As the ratio of volume to surface increases with size, the chance of a chain reaction developing in a big block is higher than in a small one.

In fact, a very big lump of ordinary uranium would be required for the chain effect to develop in it. Blocks of less than a certain critical size, specific for each kind of fissionable material, are unable to support the chain development. Uranium 235, however, which is so much more susceptible to fission, would be very much more liable to develop the chain reaction, if it could be secured in a compact block. Calculation showed that a lump of Uranium 235, weighing between 2 lb. and 200 lb. might be big enough to support a chain reaction propagated by fast neutrons. If the reaction could

be started successfully, such a lump of Uranium 235 might be expected to produce an explosion equivalent in power to that of many thousands of tons of T.N.T.

Once the reaction starts, the production of energy is sudden and enormous. The temperature rises to many millions of degrees and the pressure to hundreds of thousands of tons to the square inch. This is exerted outwards, so that the material of the lump will expand very swiftly. It will soon reach a size in which the material is so thinly spread that the neutrons can easily pass through, and escape into the air beyond. The neutrons, having escaped, will be no longer within the material and therefore will be unable to propagate the growth of the chain reaction. At that stage, the reaction will stop.

Thus it is essential that the fast neutrons should be travelling fast enough not to be overtaken too soon by the front of expanding material, otherwise most of the material will be blown apart before its atoms can be disintegrated, and its available atomic energy liberated. This would correspond to defective " explodering " in an ordinary explosive, in which the charge is blown apart before most of it has had time to explode. Calculation indicated that the fast neutrons released in Uranium 235 disintegrations would probably be travelling fast enough to accomplish the disintegration of a substantial portion of the lump before the remainder of it was blown apart. If the atoms in only one pound of the lump were fissured, the release of energy would be equal to that in an explosion of 8,000 tons T.N.T. Thus Uranium 235 might form an explosive 17,000,000 times as powerful as T.N.T.

As the lump of atomic explosive must be larger than a certain minimum size in order to support the growth of the fission reaction, it was evident that an atomic bomb could be made with complete safety, as it was only necessary to manufacture the Uranium 235 in portions smaller than the critical size. Further, all that was necessary to explode an atomic bomb was to arrange that two portions of Uranium 235, each smaller than the critical size, but together greater than the critical size, should be brought into close contact by some mechanical contrivance.

PREPARATIONS FOR PRODUCTION

The outbreak of war concentrated attention on the possibilities of atomic energy as a new catastrophic weapon, rather than a source of unlimited power that might lighten the burden of man, and provide him with vast new means and happiness. The Allies had

to explore the possibilities, not only to try to secure the new weapon for their own aid, but to forestall the enemy.

In April 1940, before the U.S.S.R. and the United States had entered the war, a committee of scientists was set up in the British Air Ministry under the chairmanship of Thomson, to report on the present state of knowledge concerning the possibility of making atomic bombs ; to co-ordinate the various researches on the subject ; advise whether such a project seemed feasible, and, if so, whether it would be possible to solve the technical problem of producing such bombs for use within the period of the war, and whether the military results of their use would justify the diversion to their manufacture of the necessary abilities and resources from other extremely urgent war work.

Chadwick at Liverpool had begun the atomic measurements needed to decide whether an atomic bomb was feasible, and, if so, what its minimum size would be. This work was hastened by a group of collaborators among whom Frisch and Dr. J. Rotblat were the senior members. Frisch had done important work at Birmingham before he went to Liverpool. As the investigation grew, scientists in other universities were invited to join in the research. Besides bringing more abilities and resources to the problem, this had the advantage of dispersion at a time when Liverpool and other centres were being attacked by the enemy's air force. The laboratories at Liverpool were in fact slightly damaged by enemy bombing. Dr. (now Professor) N. Feather and Dr. E. Bretscher at Cambridge joined in the experimental work on the determination of nuclear data. Peierls at Birmingham, assisted by Dr. K. Fuchs and others, used the data provided by Liverpool and Cambridge to estimate the critical size of the bomb. They investigated the theory of the reaction, in order to calculate how much energy might be released, and to discover the conditions under which this amount might be increased.

In this way the experimentalists and theorists collaborated to provide the data for the engineers who might have to design and make the mechanism of the bomb. This, however, was only a part of the problem. In addition to proving that the bomb was theoretically possible and might be effectively designed, it was necessary to show that the materials needed to make it could be obtained. Uranium 235 was the material required. Could this be got ? Ordinary uranium, which is itself a rather rare element, contains only 0.7 per cent of Uranium 235. Before the war, the annual world production of uranium ores contained only about 100,000 lb. of the metal. This could contain only about 700 lb. of Uranium 235.

The preparation of pure ordinary uranium compounds from a sufficiency of ores would be a very big task in orthodox mining and chemical refining, involving many improvements in methods of handling uranium ores which had not previously been called for, owing to absence of large demand. But these problems, though vast, would be quite overshadowed by the difficulty of separating Uranium 235 from ordinary uranium.

It has been mentioned that the chemical properties of atoms depend on the number and arrangement of the electrons circulating round their nuclei, and that this number depends on the size of the positive charge on the nuclei. The electrons are relatively very distant from the nucleus, and only slightly affected by variations in its mass. Hence, atoms with the same nuclear charge, but slightly different masses, cannot be separated by ordinary chemical means, except in some cases, by exploiting the slight chemical differences by very refined methods of chemical separation. In general, any means of separating atoms such as Uranium 238 and Uranium 235 will depend directly on the physical difference in mass of the two nuclei, and not on chemical differences between compounds made from them. Physical methods have been devised for separating such atoms for purposes of fundamental measurement and identification. The quantities so separated are, in general, very small and utterly insufficient to prepare even one pound of material.

One method of separating atoms of the same chemical kind but different mass is to project the mixed beam through an electric and then a magnetic field. Suppose a beam of atoms of the same chemical kind but two different masses is emerging from A in Fig. 44, and runs into an electric field at E, the slower atoms of each mass will be deflected more than the faster ones of the same mass. The beam will be split into streams diverging between R_2, R_1. Suppose now that the streams run into a magnetic field at M the slower atoms will be bent back further than the faster ones of the same mass. By suitably adjusting the electric and magnetic fields,

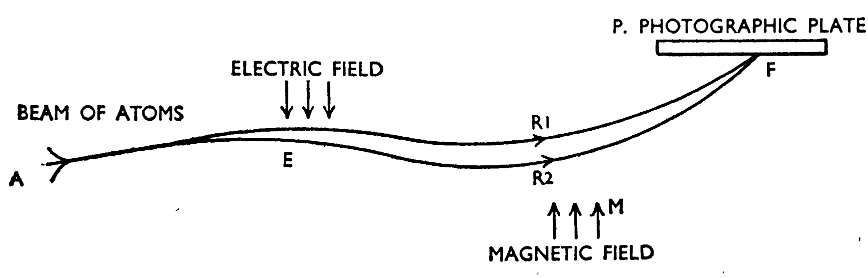


FIG. 44

the two beams can be brought together again at F on a photographic plate.

You may wonder how that helps. What is the use of splitting the beam and bringing the parts together again ? It happens that if the beam contains atoms of different mass besides different speeds, those with different mass do not focus on the photographic plate at the same point, but at points F_1, F_2, etc., as in Fig. 45.

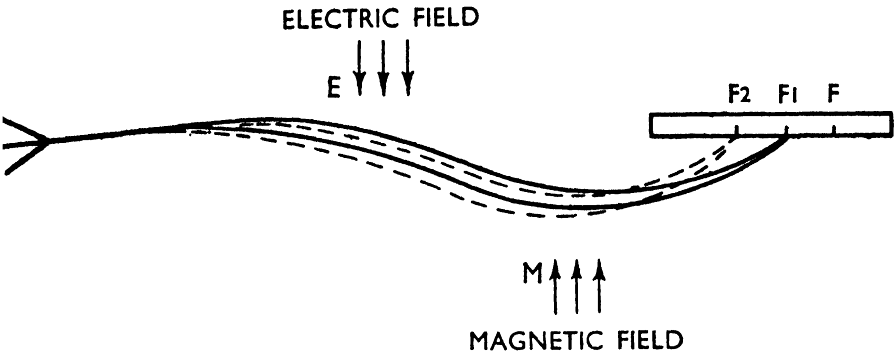


FIG. 45

The masses of the atoms making lines F_1 and F_2 may be calculated from a measurement of the distances of F_1 and F_2 from a line F, made by atoms of known mass. Using more technical language the electric field sorts the energies, and the magnetic field sorts momenta and hence for the same energy it sorts masses.

This apparatus, developed by Dr. F. W. Aston on principles of atom separation first successfully used by Professor J. J. Thomson, has made a very notable contribution to the building of modern atomic physics. It has produced a large quantity of fundamental physical data. But it does not, in its laboratory form, generally separate atoms except in extremely small quantities : just enough to make an impression on a sensitive photographic plate, perhaps after hours of exposure. The mass-spectrograph, though brilliant as a scientific instrument, seemed about as hopeless for separating practically useful quantities of isotopes as a radio beam now appears to be for transmitting electrical energy at the rate of 1,000,000 horse power from London to New York. However, in 1934, Oliphant and others at Cambridge succeeded in separating small but sensible quantities of lithium atoms of differing mass by this method. Many other methods of separating isotopes, atoms which have the same place or properties in the chemical order of things

but differ in mass, have been developed in recent years. For instance, the distillation of liquids consisting of mixtures of molecules, some containing one isotope and others another, can be employed. The molecules containing the lighter isotopes distil slightly differently from those containing the heavier isotopes. They may be separated in some cases by electrolysis. Ions containing a heavier isotope will travel through a liquid exposed to a steady electric field at a slightly slower speed than ions containing a lighter isotope. This method has been developed to separate the isotopes of hydrogen on a commercial scale. Vast quantities of water have been electrolysed, and separated into " light water " and " heavy water," the former containing hydrogen atoms of mass 1 only, while the latter contains hydrogen atoms of mass 2 only.

The rate of diffusion of gases depends, among other things, on the mass of their molecules. Hence, gaseous diffusion may be employed to separate gaseous molecules containing different isotopes. For instance, ordinary chlorine gas contains large fractions of two chlorine atoms of different masses. Chlorine can be separated by diffusion methods into two parts, one containing the heavier of these atoms, and the other the lighter.

Then there are chemical exchange methods, depending on principles similar to those on which water-softeners operate. The isotopic atoms of one element are sorted out in a solution, through slight differences in their rates of chemical exchange. A comprehensive swapping takes place, to the effect that the desired atoms of higher mass concentrate in one place while those of lower mass concentrate in another.

Yet another method depends on thermal diffusion. If you have two vertical parallel walls, one hot and the other cold, and between them a gas containing two kinds of molecules, one heavy and the other light atoms of a particular element, the molecules containing the heavy isotope will tend to concentrate on the cold wall, and the molecules containing the light element will tend to concentrate on the hot wall. This will be due to the difference in diffusion due to the difference in motion of the molecules of different weight at the same temperature. Together with this, there will be a convection of the cold gas downward along the cold wall and of the hot gas upward along the hot wall. Thus, two streams of gas of different concentration will be established, with the heavy constituent tending to collect at the bottom and the light at the top. This arrangement is very effective, but it depends on the possibility of obtaining compounds of the desired isotopes in gaseous form.

Yet another method consists of whirling vapours containing isotopes in a powerful centrifuge. The heavier molecules accumulate near the rim of the centrifuge, while the lighter accumulate near the axle. If the axle is hollow, the vapour near it may be sucked out, and thus a specimen containing more than the ordinary proportion of light atoms be secured. It has been suggested that a fractionating column should be whirled in this way, so as to obtain a combined effect of fractionation and centrifugation.

In 1940, Professor H. C. Urey, then of Columbia University, New York, the discoverer of " heavy hydrogen," in a review of methods of isotope separation for the Physical Society of London, pointed out that the chemical methods of separating isotopes are best adapted to the light elements. The methods of thermal diffusion might be applied to the heavy elements, if suitable gaseous compounds of them were available. He remarked, however, on the possibilities raised by recent work of L. P. Smith and J. W. Scott on the production of intense beams of metallic nuclei. It seemed to him that these should be adapted for use in mass-spectrographs for the separation of isotopes, and should make the effective separation of practicable quantities of metallic isotopes possible.

The Thomson Committee reviewed these various methods of separating isotopes, and considered which might be the most suitable to use under British circumstances for the separation of Uranium 235 from ordinary uranium. They had to take into account not only the scientific effectiveness of the method chosen, they had also to consider its economy, and requirements in manpower, and material, technical and industrial resources. Britain was strained to the utmost by her war-effort, and what she gave to one urgent new task had to be taken from others also extremely urgent.

The Committee concluded that the gaseous diffusion method was the most promising, in the circumstances, for large scale production. Its principles had long been known, and there existed in the chemical industry a fund of knowledge and experience in its use in large projects. The calculations for the design of the plant would not be unduly difficult, and it seemed that it would make the least demand for highly-skilled craftmanship and engineering production, which at the time were in very short supply.

Research on the possibilities of the method was undertaken in the Clarendon Laboratory at Oxford, under the direction of Simon. He and his collaborators were assisted on the theoretical side by Peierls and his group, and on the chemical side by Professor W. N. Haworth of Birmingham, the famous organic chemist and Nobel

laureate. Some experimental research was also started at the Imperial College in London. The Metropolitan-Vickers Electrical Company Ltd. and Imperial Chemical Industries Ltd. were consulted on the engineering and technical aspects of the problem.

By the early Summer of 1941, the Committee concluded that the manufacture of atomic bombs of unprecedented destructive power was feasible. The critical size of the bomb had been calculated to within a factor of three, the optimum size had been estimated, and the methods of assembling the material for use, and of fuzing it, had been considered, though no experiments had yet been made on these points.

A scheme for preparing the required material in the necessary quantities by gaseous diffusion had been proposed by Simon and Peierls, and had proceeded to the first stage of design. Industrial experts agreed that it appeared practicable. It had become possible to make a fair estimate of the magnitude of the industrial effort that would be needed to accomplish the project.

A great deal remained to be done. More precise nuclear data were required in order to deduce the critical size of the bomb more exactly and methods of assembly and fuzing had to be worked out practically. But by far the major problem was presented by the design and construction of the plant for the production of the material, and this was only in the early stages of development.

The Committee summarized the position, and on July 15th, 1941, reported that, in their view, the manufacture of atomic bombs was definitely feasible and should be pursued on a large scale.

They also reported on another aspect of research on the release of atomic energy, being pursued by Halban and Kowarski. These physicists had assisted Joliot in his experimental proof that three or more neutrons are released in each fission of a uranium atom. Several of these neutrons were fast. Joliot therefore decided to try to reduce their speed by surrounding them with a material that might act as an elastic atomic buffer. The slow neutrons were known to be more effective producers of fission, and at the same time, as they did not move so fast, the development of the chain reaction might be brought under control, so that the atomic energy could be released in a steady stream. This would be essential if it were to be utilized for civil and industrial purposes.

The most suitable substance for use as the slower-down was heavy water, so, at Joliot's request, the French Government purchased the largest available quantity from the chief supplier. This was then the Norsk Hydro Company of Norway. The French

secured 165 litres from them, which at the time formed the bulk of nearly the whole of the world's stock of this important liquid. The heavy water was brought out of Norway only just before the invasion. And before Joliot was able to make his crucial experiment in Paris, that city and France were threatened. So Joliot instructed Halban and Kowarski to escape to England with the co-operation of the British Government and in the joint interest of the Allies.

Halban and Kowarski were assisted by the British to carry their precious materials through the French countryside to a port on the Bay of Biscay. They and their cargo were on one of the last ships to sail before the completion of the occupation of France. In England they were provided with research facilities at the Cavendish Laboratory, Cambridge. In December 1940, they were able to report experimental evidence that if a system of uranium oxide, or of uranium metal surrounded by heavy water, were sufficiently big, a sustained fission reaction might be secured. It appeared that not more than a few tons of heavy water would be necessary if the uranium metal system were used.

In their report of July 15th, 1941, the Thomson Committee expressed the view that though this research was of great potential interest with regard to the production of power for civil and industrial purposes it did not promise a practical result within the period of the war. It had, however, features of military interest different from those of the fast-neutron project of Frisch and Peierls, and Chadwick ; for the slow neutrons produced by the uranium and heavy-water system would transmute many uranium atoms into the new element plutonium, which, on the Bohr-Wheeler theory might well have suitable fission properties. It should be possible to extract the plutonium from the uranium and heavy-water system by chemical treatment, and use it as a material alternative to Uranium 235 for atomic bombs. But many tons of uranium and many tons of heavy water would probably be necessary and the production of the latter would especially be a fresh major industrial effort. Thus the construction within a practicable period of time of a slow-neutron system for producing explosive plutonium, as well as a steady output of power, did not seem feasible.

While these activities were proceeding in England, American scientists had in the same period, April 1940 to July 1941, been investigating the problems of the exploitation of nuclear fission. The Thomson Committee exchanged reports with them through the normal scientific liaison which had been established between Britain and the United States. In April 1941, Professor K. T. Bainbridge,

the authority on mass-spectrographs, and in July 1941, Professor C. C. Lauritsen, one of the leading workers in high-tension and experimental atomic physics, visited England, and attended meetings of the Thomson Committee.

The Committee's Report of July 15th was referred to the Scientific Advisory Committee of the War Cabinet, whose Chairman was then Lord Hankey.

The Directorate of Tube Alloys

The Scientific Advisory Committee endorsed the Thomson Committee's findings, and on their advice, the War Cabinet decided to proceed with the project. Mr. Churchill asked Sir John Anderson in September 1941, to supervise the project as of great urgency and secrecy. Sir John Anderson had special qualifications for this task since, in his youth, before he joined the Civil Service, he had done research in chemistry, and in particular on the chemistry of uranium compounds. He formed a Consultative Council, of which he was himself chairman, to advise him on the project. In addition to himself, the original members were Lord Hankey, Sir Henry Dale, Sir Edward Appleton, Lord Cherwell and Lord Brabazon. The administration of the project was entrusted to the Department of Scientific and Industrial Research under Appleton. A new division of the Department was formed and given the title of the Directorate of Tube Alloys, in order to conceal the nature of its work.

Mr. W. A. (now Sir Wallace) Akers of the Imperial Chemical Industries, Ltd., was released at Sir John Anderson's request to direct Tube Alloys. Akers formed a Technical Committee of which he was chairman, for his advice. Besides himself, the members were Chadwick, Peierls, Halban, Simon, Dr. R. E. Slade and later Sir Charles Darwin, Cockcroft, Oliphant and Feather. Mr. M. W. Perrin was Secretary.

On October 11, 1941, President Roosevelt wrote to Mr. Churchill suggesting that the respective efforts in Britain and the United States might be co-ordinated or even jointly conducted.

In November, 1941, Professor G. B. Pegram and Urey visited England to study what had been done under the Tube Alloy project, learn the programme of future work and agree on arrangements for complete and rapid exchanges of information. Under Tube Alloys the work in England was greatly extended and after Pegram and Urey returned to America the effort there was greatly intensified.

At the beginning of 1942, Akers, Halban and Peierls and Simon visited America with the aim of co-ordinating as efficiently as

possible the British and American programmes. It was already clear that the new American Tube Alloys organization intended to utilize the resources of American universities and industry on an enormous scale.

It was evident in 1942 that the resources available for the Tube Alloy project were much smaller in Britain than in America. Apart from the difference in size in the two countries, a much larger proportion of British scientists and industrial resources were already mobilized on war work. Consequently, it was decided to limit the Tube Alloy programme in Britain. This was broadly restricted to experimental research on nuclear data ; theoretical studies of atomic chain reactions, the design of the bomb and its blast effect ; experimental and theoretical studies of the gaseous diffusion process for separating Uranium 235 ; the design and construction of prototype machines, etc. ; the study of slow-neutron systems, especially those of the uranium and heavy-water kind ; the manufacture of uranium metal for use as " piles " in which uranium is converted into plutonium with the release of atomic energy under controlled conditions ; and the manufacture of heavy water.

The Metropolitan-Vickers Electrical Company Ltd. made certain prototype machines according to principles worked out by Simon and Peierls. Imperial Chemical Industries, Ltd., undertook the very extensive programme of developing the gaseous diffusion plant as a whole, designing the plant, working out the complicated flow-sheets governing the circulation of materials in the plant, conducting research on novel materials of construction, etc. Imperial Chemical Industries (General Chemicals) Ltd. worked on a method of manufacturing uranium metal for the " piles " for the steady atomic power release systems.

The British authorities decided that no full-scale production plants should be built in Britain at that time. Resources in Britain were already completely concentrated on the war effort, further major production could not be undertaken. Britain was also within easy range of the enemy. Factories could be bombed, or even raided by enemy troops from air and sea, or attacked by new weapons. But in the United States, the factories would be free from these dangers. The reality of these dangers was shown by our own success in attacking the Norsk Hydro Plant, from which Joliot and his colleagues had secured their stocks of heavy water. When the Germans captured Norway, they used this plant for supplying heavy water for their own atomic bomb researches. Their scientists had discovered the fission effect, and there were others of

the highest genius who might discover the further scientific secrets. They worked hard, and made considerable progress. The Allies therefore had to exert every effort to learn their progress, and interfere with it. Two Anglo-Norwegian commando raids were made on the Norsk Plant and its supplies of heavy water. The plant was seriously damaged and stocks of heavy water being sent to Austria for atomic bomb research, were sunk in a fiord. In these actions Professor Leif Tronstad, the professor of physical chemistry at Trondjem, who was familiar with the plant, fought as a Norwegian commando captain, and, with many other brave men, lost his life.

Some of the raw material for the project was purchased under contract from the Canadian Government, from greatly extended uranium ore mines in Northern Canada. At the end of 1942 it was decided to move the slow-neutron research under Halban at Cambridge to a place nearer to Chicago, where the corresponding American research was in progress. Accordingly, Halban and other members moved to Montreal, where the Canadian Research Council established a large research laboratory for the investigation of the controlled release of atomic power. This Anglo-Canadian enterprise was strengthened by the addition of many Canadian scientists.

In the spring of 1944 it was decided to construct with American help a uranium and heavy water power plant. The site, which was on the Ottawa river, was provided by the Canadian Government, who also built the laboratories and purchased the material. Heavy water was supplied by the American government. At this time, Cockcroft succeeded Halban as director.

Sir John Anderson visited America in August 1943, to plan the co-operation between Britain, Canada and the United States. Chadwick was appointed Scientific Adviser to the British members of the Combined Policy Committee, and moved to America. Many of the scientists working on the Tube Alloys project, together with others, were also moved to America and joined the corresponding groups there. Oliphant, who could now be spared from his radar researches at Birmingham, moved with a team to work at Berkeley, California, with Lawrence, who had made remarkable progress in the engineering development of isotope separation by mass-spectrograph. Bohr escaped at this time from Denmark, became a scientific adviser to the British Government, and then moved to America. He was one of the last to escape and he left Denmark in a fishing boat, with several members of his family. He sailed to Sweden in the extreme stillness of a misty evening, and had to

leave a baby grandchild behind for fear its cries might be heard in the quiet darkness. Then he was flown to London doubled up in a corner in a Mosquito plane. Frisch, Peierls and others joined the great American Tube Alloys establishment at Los Alamos.

HISTORY

What, then, have the British contributed to the discovery of the atomic bomb and the release of atomic energy?

Through Rutherford and the British school of atomic physics, they made the major contribution in the sphere of fundamental physical knowledge of the atom. Chadwick has expressed the opinion that in 1941, Britain led the world in the preliminary research and development. In 1943, however, America had secured the lead. Her research and development groups were then joined by some 75 other British scientists.

Scientists in Britain became confident in the possibilities of the atomic bomb at about the time when the importance of radar had become thoroughly appreciated, and brilliant short-wave developments were in progress. Britain was fighting for her life, and radar offered the most immediate aid, however great the potentialities of the atomic bomb might be. Hence, many of her leading atomic physicists concentrated at first on radar. Cockcroft, Oliphant and others, after leading distinguished work on radar, subsequently had an equally distinguished part in developing atomic energy.

The War Cabinet had to decide whether to take many of the leading physicists from radar, on which the protection of the country and our offensive power depended, and put them on to a project potentially decisive, but obviously requiring much development, and still imperfectly understood in detail. Necessarily, the first priority was given to radar.

Considering the situation in 1941-43, the success of scientists in Britain, in not only developing radar but coming to the right scientific conclusions about the atomic bomb, was extraordinary. It was a double exhibition of fundamental scientific judgment.

But on the departure of the group of British scientists to America in 1943, research in Britain on nuclear physics virtually ceased, research on electro-magnetic separation ceased for a time, and the gaseous diffusion plant at Billingham virtually closed down. The huge task of designing and building the actual manufacturing plant and making the actual bombs was done entirely by America, at a cost of more than £500,000,000. President Roosevelt and his advisers had the courage to spend this sum, incomparably the

greatest ever given to the achievement of one single object, on a project for which no previous experience existed. Their confidence was based entirely on the formulae and experiments of science. The British contributed the whole of their intellectual inheritance in nuclear physics to the pool. They contributed notable developmental work. But in Britain no plant for producing atomic bombs and releasing atomic energy existed. Her physicists were dispersed and her engineers almost entirely engaged on other things.

IV.

SCIENCE AND THE SEA

Ships move in the surface that separates the world of water from the world of air. Ever since they were invented, they have been subject to invisible forces. They are blown by winds, and carried by currents, that cannot be seen. They are dependent on what happens in the water and air which share their existence, and on what can be done in these media.

What are ships for ? They are used by man to place himself, in spite of water, where he wishes to be, for the purposes of pleasure, trade or fighting. He designs ships, in accordance with the properties of the media in which they operate, for such ends.

The first need in a ship is that it should float. This primitive requirement seems almost like a fact of nature. But in this war it has led to difficulties in the design and use of certain invasion craft, which were to be sunk on the enemy coast. The men of the sea, with the tradition that, whatever happens, they must keep their ships afloat, did not always take kindly to the idea of ships designed to be sunk.

For the ship to float, the forces acting on it due to the hydrostatic pressure of the water and to gravity must be equal ; for the ship to be stable the centre of pressure must be in the same vertical line as the centre of gravity, and when the ship is slightly disturbed the centre of pressure must move so that the combined hydrostatic and gravitational forces tend to restore the ship to her original position. This must apply in rough beside fair weather, when the water is whipped into waves by the wind.

A ship must have superstructure, or freeboard, and draught to give protection against the weather and provide space for stowage. The ship when floating displaces a volume of water of weight equal to the weight of the ship itself. Ships are generally large compared with, say, aircraft partly because of the weight of water, 64 lb. per cubic foot, yet if water weighed half as much per cubic foot as it does, a ship to carry the same load would need to be twice as large.

One of the fundamental features of the use of science at sea arises from the size and weight of ships. The equipment is often large, heavy and expensive and new weapons often cannot be introduced quickly. The general adoption of a new gun in ships usually takes three years.

In contrast, aircraft are in general much smaller and lighter than ships. Hence change and evolution in them is in general less expensive, and the problem of production is less difficult. Fundamentally, the difference arises from the fact that water is a liquid while air is a gas.

THE CHOICE OF WEAPONS

Owing to the problems of size, the introduction of new naval equipment usually cannot be swift. Hence the navy which has had most foresight and has done most preliminary research in peace will have a particular advantage in war. Any lead that is established in peace-time will tend to be held in war. This has been confirmed by experience. On the whole, those countries which specialized on a particular line of research before the war remained ahead in that line throughout the war.

The choice of lines of research depends on the decisions of the naval chiefs of staff. In each country the naval staff draw up a list of priorities in scientific research according to the strategical situation, resources and other general considerations. Thus the aims and circumstances of different countries generally prevent them from directing equal efforts to exactly the same problem. Britain, for instance, has an immense merchant fleet. Any enemy intending to attack her would give particular attention to the development of weapons for attacking merchant ships. One of these is the offensive submarine, with its torpedoes. The British would naturally give special attention to research on anti-submarine devices.

In general, the Germans at the beginning and at the end of the war were in front in the design of offensive submarines and torpedoes, while the British at the beginning and at the end of the war were in front in the design of anti-submarine devices.

These experiences confirm the importance of far-sighted peacetime fundamental research on science at sea. Once one has fallen behind in any naval scientific field, it is very difficult to catch up again.

DETECTING SUBMARINES

The first step toward the attack and destruction of submarines is their detection. As they move and attack under water, the

properties of the under-water world must be utilized in order to discover them. One cannot see far through sea water, so light is not of primary use. Radio cannot be used for detecting submerged submarines, as radio waves are absorbed by water. One possibility is sound, for water conducts sound well. Sound proves to be the most suitable instrument for detection of submerged submarines, for over a broad band of frequency the sound is conducted with very little loss and these frequencies are fortunately such that beams of sound are readily formed.

For detection of a submarine on the surface, radar gives very satisfactory results, since, with very little loss radar waves can be transmitted in suitable beams through the air.

The type of detection must be chosen according to the physical properties of the medium. It is for this reason that military scientists need the utmost fundamental knowledge of the sea and the air.

They need to know the physics and chemistry of the sea ; the content of various gases in it and their effects on sound transmission ; the phenomena of cavitation, the holes produced in water by rapidly moving objects such as propeller blades and under-water projectiles ; the origin and properties of waves. It is necessary to study the behaviour of sound in pure water, and in the sea, and to be able to distinguish the interference from naturally produced noises coming from whales, porpoises, and even fish and shrimps. The splash of waves and the noise of tide rips add to the background in the sea and these noises are modified by reflection from the surface and bottom.

The study of the atmosphere over the sea is required in order to understand its effects on the transmission of radar, besides the usual problems of weather. Knowledge of the medium gained in peace-time ensures the most effective exploitation in time of war, but mere qualitative information is not sufficient, measurement is essential for the production of successful devices.

Ocean Echoes

The detection of submerged submarines by sound has been particularly highly developed by British scientists. The method has been evolved from a suggestion made in 1912, after the sinking of the liner *Titanic* by collision with an iceberg. A British engineer named Richardson suggested that icebergs might be detected by the echo of a pulse of sound waves emitted from the approaching ship. The use of short sound waves which can be readily " beamed " like

a searchlight is necessary in order to secure precise definition of the direction of the berg. In 1914 the only known practical way of obtaining such short or supersonic waves was from oscillators made of mica and caused to vibrate by electrical stresses.

An Allied Committee was at this time formed to develop anti-submarine technique. It included Dr. R. W. Boyle, of Canada, Professor W. H. (later Sir William) Bragg, Professor P. Langevin of France, and Rutherford. Langevin succeeded in 1915 in producing ultra-sonic waves by applying the piezo-electric effect discovered by Jacques and Pierre Curie. When quartz crystals are cut in the appropriate way electrification expands or contracts them; and conversely, when mechanically stretched or compressed they produce an electric charge. Thus an alternating electric potential applied to a quartz crystal causes it to vibrate and these vibrations are of the type that produces sound waves. Hence by suspending a quartz crystal in water, and applying to it a pulse of alternating current of appropriate frequency, the crystal will be made to vibrate and communicate to the water a pulse of sound waves of the desired length. This will be transmitted through the water and be reflected by any obstacle. If such an obstacle is of sufficient size an echo can be received on the quartz which sent out the transmission. The echo creates a weak pulse of alternating current which can be detected by electrical instruments. In the spring of 1918, scientists at the Admiralty Experimental Station at Harwich succeeded with an apparatus of this kind in securing super-sonic echoes from a British submarine at a range of a few hundred yards.

The method has now been perfected to such a degree that objects as small as mines and human torpedoes may be detected at a distance of one mile. The range of the object is readily determined by measuring the time interval between the transmission and the appearance of the returned echo. The velocity of sound in water is roughly 1,600 yards a second, and a time interval of one second thus corresponds to a travel there and back of 1,600 yards, that is an actual range of 800 yards.

The development that began at Harwich was continued in research stations at Shandon, Portsmouth and Portland, and during the war at the Anti-Submarine Experimental Establishment at Fairlie on the Clyde Estuary. A great increase in our fundamental knowledge as well as much progress in the design of practical sea-going gear was made at Portland from 1927 onwards under the direction of Mr. B. S. Smith. During this period a small group of scientists and engineers, generally about 15, were able by excellent team work

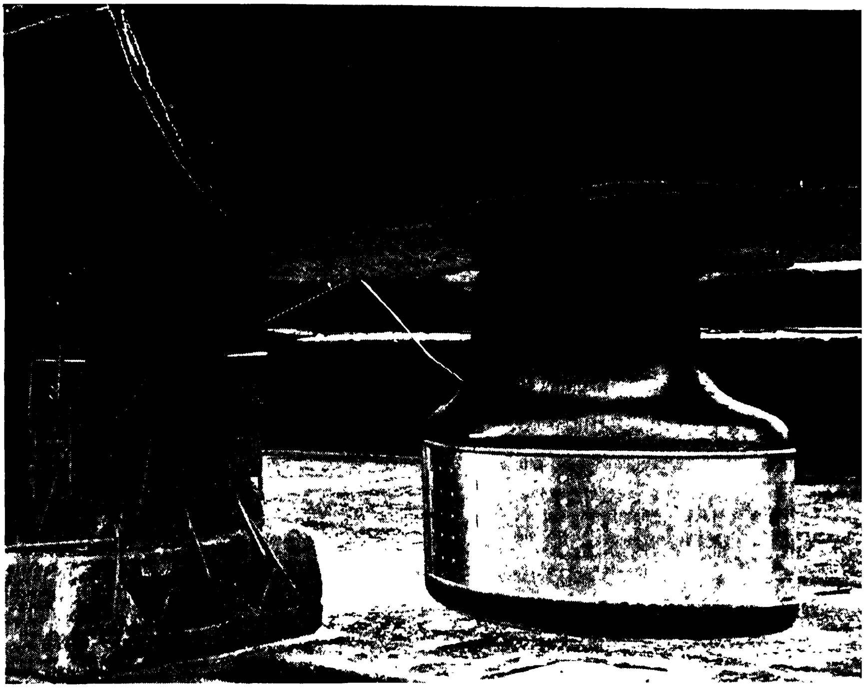
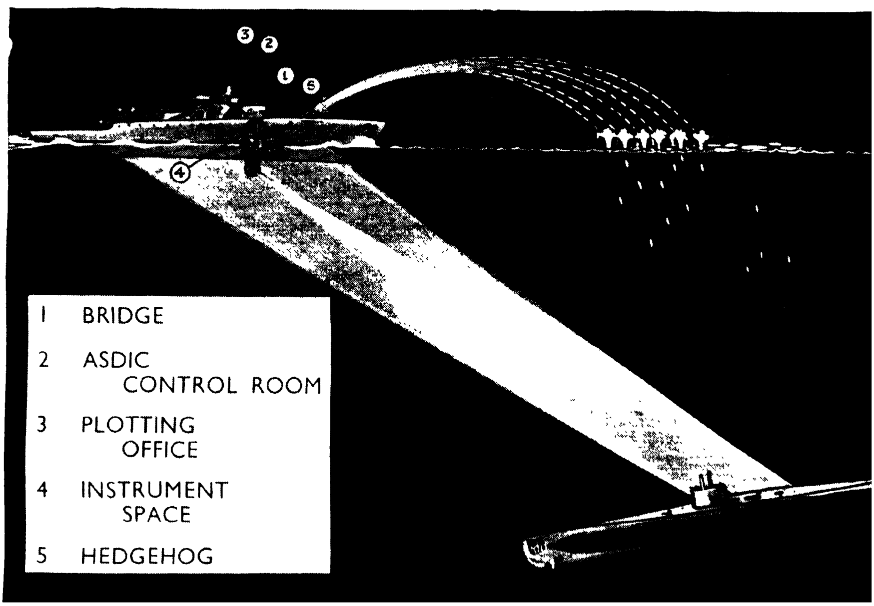


PLATE XXXIX

An Asdic dome on the bottom of a ship in dry dock is shown above. The bow of the ship is off to the left of the picture (*see* page 157).

Below is a pictorial representation of a U-boat caught in the beam of ultra-sonic waves from the Asdic dome of a corvette. The Asdic gives the range of the U-boat, and from this, the " Hedgehog " battery is fired, which discharges a pattern of bombs that sink rapidly to the depth of the U-boat, and then explode.



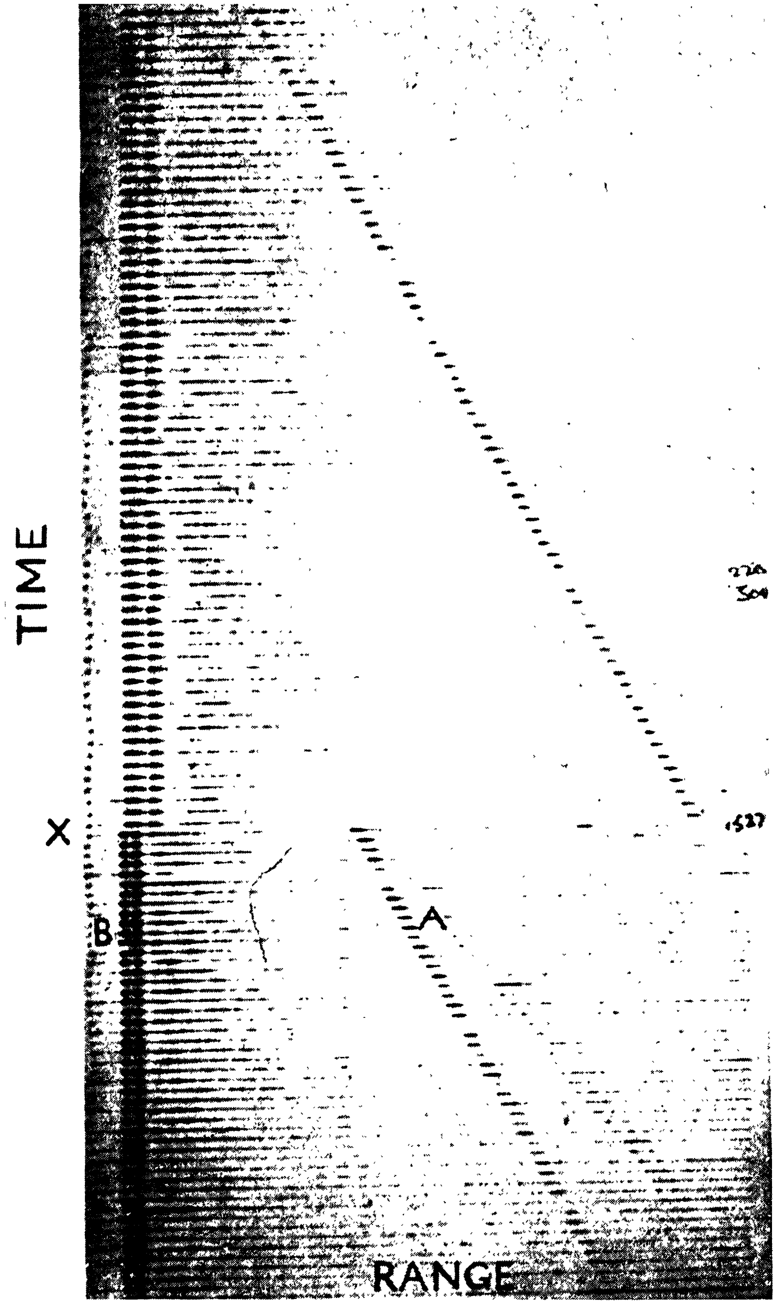


PLATE XL

Echoes from a submarine at 150 ft. depth. Range is measured by the distance of the records of the echoes, appearing as little black dashes on the right, and sloping upwards to the left, from the vertical column on the left, *i.e.* by the distance A B, etc. As the corvette closes on the U-boat, the scale is magnified from 2,500 to 1,000 yards. (X) Pulses of ultra-sonic waves are issued at a shorter interval, so that the course is determined with more accuracy.

to produce A/S equipment for the Navy which was far in advance of that possessed by any other nation at the outbreak of war in 1939.

The design of the quartz transmitter was improved by a long series of researches. The form in general use at the outbreak of war consisted of a quartz steel sandwich with steel plates of thickness to suit the operating frequency. The emitting face was 15 inches in diameter, the size having been chosen as the most convenient after experience with oscillators of various diameters from 10 to 24 inches. The choice of frequency was made after very thorough studies of the behaviour in water of sound-waves of various lengths.

These researches were greatly facilitated by the development in 1925 of a signal strength meter covering a wide range of frequencies and a range of maximum to minimum signal strength of over 100,000 to 1 in amplitude. With this aid, it was found that super-sonic waves of frequency 100,000 per second are attenuated as much after passing through 50 yards of water as waves of frequency 10,000 after passing through 1,000 yards of water. For general purposes, a frequency in the region of 20,000 per second is the most useful.

Then it was necessary to determine the minimum power required for the transmission. It was found that a transmitter producing about 50 watts of sound-power in water was adequate. This would give echoes under average conditions in the water from submarines at 5,000 yards. If this power is increased four-fold, the gain in range is only 10 per cent. To double this range, a million times more power would be needed.

The behaviour of high frequency waves in water has been studied by direct experiments in the sea, besides in the laboratory. The influence of surface waves and weather, and of the temperature and saltness of the water, on the behaviour of the sound waves has been carefully studied. In 1922 an expedition consisting of a destroyer and a submarine was sent to the Mediterranean, to make experiments on the effect of temperature and saltness on the range of detection of submarines. This expedition was followed by many others in the main oceans of the world, and by this means information of the highest tactical and strategical value was obtained.

Observations under the Sea

The invention and development of a quartz transmitter which will send out pulses of sound waves through the water and receive their echoes back was only a part of the task. The transmitter has to be carried in the water below the keel of the ship it protects

so that all round acoustic " vision " may be maintained. Without some protecting cover the movement of the transmitter through the water at high speed would set up turbulence which would refract and scatter the sound beam and set up noise which would mask the faint returning echo.

Here was one of the most formidable problems. British scientists alone seem to have solved it satisfactorily. To achieve this it was necessary to attach domes of various shapes round the transmitter and observe the performance in high-speed conditions, in cruisers, destroyers and smaller craft. In use the dome is full of water and remains fixed in relation to the hull of the ship. The transmitter is slowly rotated inside, so that the sea around the ship is continually swept by the beam of sound pulses. It is enabled to rotate at a steady speed, independent of turns of the ship, by a control from the ship's gyro compass. It is necessary for the covering of the dome to be as pervious as possible to the sound waves passing out, and the echo returning in, and yet be strong enough to withstand the water forces acting on it. The first dome consisted of a cylindrical steel frame covered by a stout canvas, but it was not effective at speeds above twelve knots owing to cavitation noise. It was followed by experiments with streamlined domes, whose length was 2½ times the diameter. They had a thin steel skin over a steel framework, and were fixed to the bottom of the ship. They would work at speeds up to 14 knots, but they were fragile, and the numerous break-downs in service almost caused the use of the echo-detection to be dropped by the Navy.

The background noises, and the forces and pressures on the domes, and their acoustic properties, with different kinds of skins were very thoroughly measured and studied. As the streamlined dome is pushed through the water, it is subjected to pressure on the front, but to suction on the sides. The destruction of the domes is mainly due to this sucking-off effect. Modern designs of dome can be used at higher speeds with safety and have adequate transparency.

The best position for the dome on the ship's bottom was found as a result of a series of investigations using a special observation dome fitted with windows and pressure-measuring devices. Scientists went through the ship's bottom into the dome to make their measurements and observations below the hull. In 1929 three domes, including an observation dome, were fitted at different places under-underneath the cruiser *Devonshire*. Mr. J. Anderson, who later became Superintendent Scientist at the Anti-Submarine Establishment, made many journeys inside the observation dome while the

ship was travelling at up to 30 knots, to observe exactly what was happening around the domes. The water passed the dome with a tremendous roar, and the features of its turbulence were noted. One dome was placed forward on the centre line of the bottom, another was slightly aft off the centre, and the third was further aft. It was found that the best position for the dome was as far forward as possible on the centre line. If it is off the centre, bubbles of air interfere with the stream past the dome.

In 1931, after years of research, the present shape and placing of the dome was perfected, and the operation speed raised from 10 to over 20 knots.

As a result of these and other courageous personal experiments the British submarine detecting device, named Asdic—after the original Allied Submarine Detection Investigation Committee, it is thought—was made uniquely effective. All our discoveries were made available to our Allies on the outbreak of war. The successful solution of these problems required a great deal of sea-going from the scientists. Some of them consequently spent much of their lives at sea, and have thoroughly learned the point of view of the Navy, which is the final user.

The early detecting devices depended on the hearing of the echo, by conversion into a current that could be passed through ear-phones. In 1930 a chemical recorder was introduced. This was based on the Fultograph, used in the earlier days of the transmission of pictures by radio. It consists of a roll of starch potassium iodide paper which is discoloured each time a current runs through it. In this way a picture can be built up. The track of the submarine in relation to the ship is automatically drawn, and from it the correct time to fire for different kinds of weapons can be accurately obtained.

The adoption of weapons which throw projectiles or charges ahead of the ship, instead of depth charges dropped from her stern, led to a great increase in effectiveness of attack. They enable the ship to fire when the submarine is definitely under aim with the aid of the Asdic apparatus. If, for example, a submarine is 450 yards away, the passage of the charges through the air will take about 11 seconds. If it is 300 feet deep, and the charges sink at 20 feet per second, they will take 15 seconds to sink to the correct depth. Thus, there will be 26 seconds of " blind " time, from the last moment that the position of the submarine is recorded, to the moment when the charges explode. The submarine has only that time for possible manoeuvre. With the old system of dropping depth charges, the chaser would have to steam 450 yards at 15

knots, and then drop the charges astern. There would be a "blind" time of about two minutes, leaving the submarine with about six times as much time for evasive action.

The introduction of the long pipe for discharging the gases from a submerged submarine to the surface, known as the Schnorkel or snout, increased the value of Asdic. The Schnorkel was invented by the Dutch engineer Gunning. He fitted a Dutch boat with a crude form of the invention. The boat was captured by the Germans through the invasion of Holland. They appropriated the idea and developed it. The exhaust snout sticking above the surface is too small to be detected easily by radar, which is so effective in revealing surfaced submarines and thus enabling them to become targets for very effective attack by aircraft. As the use of "permanently-underwater" submarines lessened the effectiveness of radar, the relative value of ultra-sonic detection was restored.

There are many forms of Asdic for special purposes ; for use in motor-launches besides larger ships ; for the assistance of submarines in offensive, besides defensive, operations ; for protecting harbours ; and for echo-sounding and other aids to navigation.

Besides conducting and devising these varied researches and applications, the Anti-Submarine Establishment made a large amount of special equipment and during the war, no less than 8,000 quartz oscillators were produced by Admiralty establishments.

From Catching Whales to Catching Submarines

The idea of the corvette arose out of visits by members of the Admiralty staff to a shipyard at Middlesbrough in 1939, before the war had started. A firm of shipbuilders were making oil-fired whalers with a range of 10,000 miles and speed of 15 knots. These ships, specially designed for hunting whales, were the prototype of the corvettes which proved much better than the slower trawlers for hunting submarines. When the need for the corvette became clear, a prototype was at hand, and no time was lost in evolving the chief features.

In 1946 the Navy came to the assistance of the whaling industry by fitting the Asdic to a whaler to assist the finding of whales in the Antarctic.

SINKING THE DETECTED SUBMARINE

The only anti-submarine weapon in service use in the Royal Navy in September 1939, was the depth charge. This had been little changed since 1918, apart from an improvement in the firing pistol which eliminated the danger of the charge being exploded by impact when thrown on to the water.

This depth charge could be set to detonate at any of six depths, ranging from 50 feet to 500 feet. It was thrown in patterns of five. Three charges were dropped from rails at the stern of the ship at a spacing of 150 feet and two were thrown sideways, aimed to fall at a distance of 150 feet from the centre charge of the previous three. The charges thus formed a four-pointed star :—

```
      X

X     X     X

      X
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The charges contained 300 lb. of amatol, and sank at 10 feet per second. The slow rate of sinking enabled the laying ship to move out of range of danger from the explosion of the charges.

The analysis of experiences in the early part of the war indicated that depth charge attacks would be more effective if the pattern consisted of two layers, one about 100 feet deeper than the other. Faster-sinking depth charges were required, and these were secured by adding a 140 lb. ballast weight to the Mark VII. This raised the rate of sinking to $16\frac{1}{2}$ feet per second. Mark VII depth charges were used throughout the war, about 202,000 being discharged.

A submarine is, in general, not destroyed unless the depth charge explodes within 25 feet of it. An explosion at 50 feet is usually sufficient to make it come to the surface, and the accumulation of explosions at greater distances may have the same result. Theoretical calculation shows that about one out of every four throws of a complete pattern should bring at least one charge within 50 feet of the submarine. Experience showed, however, that only about one throw in sixteen was successful.

The total number of German U-boats sunk by depth charges thrown from British ships was 158 ; British air and ship-borne depth charges accounted for 42.8 per cent of all German U-boats sunk.

The method of laying depth charges over the stern has two disadvantages. It is difficult to steer the laying ship so that its stern is

over the submarine, and the slow-sinking depth charges may be evaded by the submarine while they are sinking to its depth. The aiming of the depth charges can be much more accurate if they are thrown ahead of the ship, as the mortars that throw the charges are, in effect, much quicker and easier to aim than the laying ship as a whole, which has to be steered over the submarine when attack is made by dropping charges from the stern. The " blind " time, between the exact locating of the U-boat and the explosion of the charges, is very much reduced by throwing the charges ahead. This technique was energetically developed in the early years of the war. Mortars were introduced, which threw ahead 24 projectiles each containing 31 lb. of T.N.T. and fitted with contact fuzes. The shape of the projectiles was designed, on the data of experiments with laboratory models, to be very quick-sinking, and the rate of sinking was thus raised to 22 feet per second. This weapon was called the *Hedgehog*. The mounting can be rocked by hand to allow for the roll of the ship. The charges are thrown in a circle about 130 feet in diameter. Ships were fitted with this weapon from January 1942, onwards, and 48 German U-boats were sunk by it.

As the *Hedgehog* charge is fitted with a contact fuze it does not explode unless it hits the U-boat. Hence the effect of near-misses, both in damage and on the morale of the crew, is lost. Consequently, in February, 1942, the design of a weapon for throwing ahead much larger charges detonated by time fuzes was begun. A three-barrelled mortar for throwing three projectiles each was developed, and named the *Squid*. The first ship to be equipped with this weapon was H.M.S. *Hadleigh Castle*. The expenditure of ammunition required to sink a U-boat with the *Squid* was very much less than with depth charges. The production of the *Squid* was ordered direct from the drawing board in the urgency of the situation in 1943. The modifications found necessary after bringing it into service were found to be negligible. This is a striking example of the efficiency and economy of the application of thorough scientific and engineering methods to the solution of problems of weapon design.

At an early stage in the war, aircraft were employed for attacking as well as detecting U-boats. They were equipped at first with naval depth charges. These were not designed to withstand heavy impact on striking the water, and had therefore to be dropped from a low height and speed of aircraft. They were also too heavy, and were not stream-lined. A modified depth charge was accordingly introduced, pending the re-designing of the 250 lb. anti-submarine bomb. It was limited in weight to 250 lb., and produced in a

shape convenient for stowage in an aircraft. It was filled with 165 lb. of the explosive Amatol, and fitted with a tail to improve the accuracy of its flight through the air. It was equipped with a firing pistol which remained safe until the charge was released from the aircraft : this prevented aircraft-carriers from being damaged by anti-submarine aircraft containing depth charges which crashed over the side when taking-off or landing.

Analysis of experiences showed that depth-charges dropped from aircraft were not as effective as they might have been, because the firing pistols in use did not detonate until the depth was greater than 50 feet. When attempts were made to set the pistol to fire at shallower depths, it was found that the operation was uncertain, owing to the formation of a hollow or cavity by the projectile when it entered the water. This prevented the pistol from receiving the pressure of the water until the depth charge had gone deeper, the cavity had closed, and the water had come in contact with the pistol. Laboratory experiments with models led to the design of a projectile which, on entering the water, produced much less cavity, and hence enabled the firing pistol to be operated by the water-pressure at shallower depths. The tail of the depth charge was designed to break off on striking the water, and the nose was sliced so as to give the charge an overturning motion and bring its side, containing the pistol, more quickly into contact with the water. Thus the firing depth was reduced to 20-30 feet, and with further improvements to the firing pistol, to 15-25 feet. This weapon was the most effective used in the war for the destruction of U-boats, the total number sunk by depth charges from British aircraft being 179.

Special depth charges were developed for combating midget underwater craft. These were made light enough to be man-handled in light motor boats. They weighed 100 lb. and contained 55 lb. of the explosive Minol. They were used in considerable quantities to repel attacks by midget submarines on the invasion area and on the east coast, in the last stages of the war.

The improvement of explosives during the war led to the increase in the destructiveness of depth charges. From January 1943, all Mark VII depth charges were filled with Minol, and this explosive was also used in the *Hedgehog* projectiles, and depth charges dropped from aircraft were filled with Torpex. These explosives were about 50 per cent more effective than T.N.T., and conferred this degree of improvement on the weapons in which they were used.

The earlier forms of firing pistol were operated by the water-pressure acting through a hole or orifice. It is evident that if a

certain pressure is needed to operate the pistol, a relatively large area of the pistol must be exposed to the water-pressure at a shallow depth, while a small area will be sufficient at a great depth. Hence the depth charge can be made to explode at a shallow depth by exposing the pistol to the water-pressure through a large hole, and it can be made to explode at a great depth by exposing the pistol through a small hole. It is found, however, that the hole becomes too small to be practicable at depths below 850 feet. At the end of the war U-boats dived sometimes to 900 feet, so a new kind of pistol mechanism for very deep depth charge detonation was introduced. This depended on the shearing of a pin exposed to these greater depth pressures.

Since depth-charges were by far the major part of anti-submarine armament carried by ships, the methods of handling them were studied and continuously improved, in the direction of mechanization. The need for accuracy in attack required that time should be saved, and human mistakes eliminated. These were achieved by automatization. A depth-charge pattern control system was finally developed in which the sequence of operations of timing and firing of the patterns of projectiles is governed by a clock. This released the charges and the throwers at the appropriate times through electrical contacts with the rail along which the charges run. It enabled the time of reloading of a pattern of projectiles to be reduced to 2 minutes, and four patterns to be discharged successively with three 2-minute intervals, or in about 6 minutes altogether.

THE MAGNETIC MINE

Magnetic mines were devised for the Admiralty under the direction of F. E. Smith, now Sir Frank Smith formerly Director of Scientific Research at the Admiralty and Secretary of the Department of Scientific and Industrial Research, during the war of 1914-1918, and were developed by the Naval Mine Design Department. Some were laid in the North Sea. When magnetic mines were first used by the Germans in the second world war, a quarter of a century later, Smith was present at the Admiralty meeting which discussed how they should be met.

Ever since the first world war studies had been made on the magnetic properties of ships, and how they could be used for defence and attack. Since a steel ship behaves as a magnet, its approach may be detected by its magnetic effects.

This feature was brilliantly applied by Mr. S. Butterworth of the Admiralty Research Laboratory and others, to the development of

systems of wire loops for protecting harbours against approach by hostile ships, submarines, and midget submarines ; and to the development of leader cables for guiding our own ships into protected harbours. In principle, a harbour is protected by a main loop. This consists of a cable which is connected to a galvanometer ashore. The main loop (see Fig. 46) is connected to a galvanometer

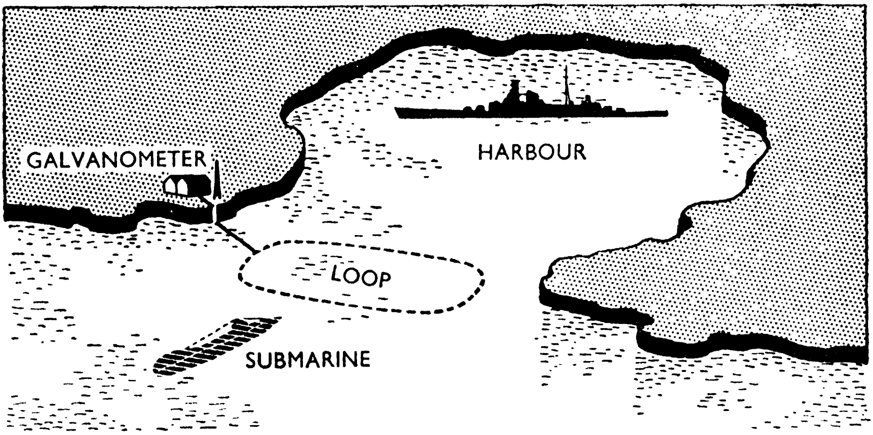


FIG. 46

in an observation station on the shore. The developed system is complex. Guard loops are laid just ahead of the main loop to give a short warning. Beyond them, further out to sea, there are indicator loops to give early warning. The currents induced in the loops are very small. Extremely good amplifiers were developed to magnify them sufficiently. Much research was necessary to devise systems of loops that are unaffected by magnetic disturbances from electric trains, etc. ; and to interpret correctly the meaning of the currents observed.

It is evident, too, that the magnetic properties of a ship might be exploited to defeat various weapons of electrical kinds which might be used against the ship. In 1936 the Admiralty appointed a committee to consider measures that could be taken against such devices. One obvious method was to neutralize the ship's magnetism, so that there would be nothing to activate the magnetic devices.

It will be seen that much important and successful research on ship magnetism had been achieved since the war of 1914-1918. It was not, however, primarily in the direction of measures against magnetic mines.

Many naval authorities formerly regarded the mine as essentially the weapon of a lesser naval power. This strategical reason tended to deflect attention from the study of mines in general, both from the scientific and the tactical point of view. Perhaps, following from this, and from a belief that mines laid on the sea-bed would be too far from the ship to be detonated by it, and too far to do serious damage even if they were detonated, the British were mainly interested in the buoyant mine, and paid less attention to the possibilities of mines laid on the sea bed. As the buoyant mine explodes on contact with, or close to, the ship, it seemed unlikely that demagnetization would be a satisfactory protection against buoyant magnetic mines ; and even less against other magnetic weapons. Experiments were therefore made on *increasing* the magnetic field of ships, so that magnetic weapons would explode at a distance, before they came close to the ship. In 1937-1938 H.M.S. *Curacoa* was wound with various coils in order to produce such effects. Laboratory investigations, which became one of the bases of much subsequent research, were made with a scale model of the ship. In March 1939, a system of electro-magnets was designed for placing in ships which could give them an extra strong magnetic field, and hence enable them to explode magnetic weapons at a distance. The equipment was not primarily intended to explode mines laid on the sea bed and was not particularly suitable for that purpose.

In September 1939, the Germans began to lay mines which exploded without contact, and were also not buoyant. By October, it seemed almost certain that these were magnetic, but no specimen had been obtained. Though the anti-magnetic weapon equipment had been designed primarily for other purposes preparations were

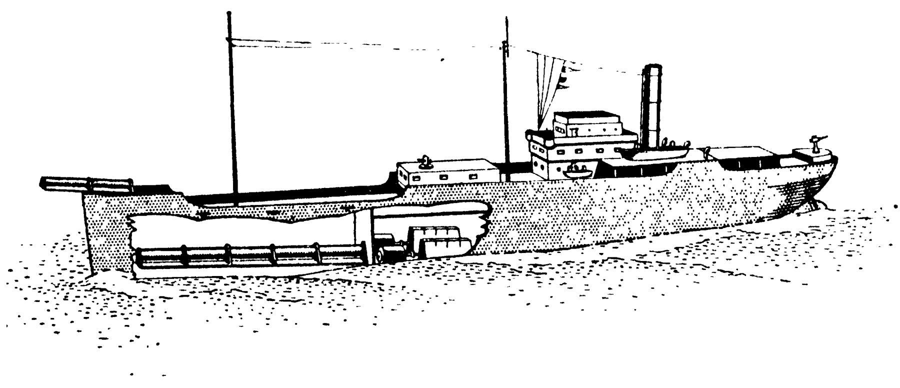


FIG. 47.—Diagram of a ship fitted with powerful magnets to detonate magnetic mines.

made for fitting the ship *Borde* as a magnetic mine sweeper, with a great electro-magnet weighing 400 tons. The core consisted of a bundle of steel rails 200 feet long. In November, 1939, the Germans began a new campaign of mine-laying by aircraft. On November 23rd one of the non-contact mines was at last secured ; it proved to be a magnetic mine. Though some scientific research had been done, no working sweepers for disposing of magnetic mines actually existed. A tremendous effort of improvisation became necessary. It was successfully achieved, but only by a number of new and additional efforts.

A Crisis

The German mine-laying campaign of November 1939 had two major features. The first of these was technical, and consisted of the use of magnetic mines that rested on the sea-bed and were detonated, without contact, at relatively great distances, by passing ships.

The second major feature was the tactical use of these mines. They were laid by aircraft in harbours and shipping channels, where the water was fairly shallow, so that they would not be too deep to be fired by the passing ships. Our shipping services would thus be hit where they were most concentrated and most susceptible to damage.

This tactical employment added to the technical complication caused by the use of non-contact mines, and the dropping of mines from aircraft. Hence many of the things that happened seemed strange and surprising. A sea-plane landed in Harwich harbour, put out mines and flew away. Other mines were dropped by parachute.

The Germans had much success. About one out of every four mines did damage, and the amount of shipping sunk was alarming. One of the first useful counter-measures was the guidance of shipping into protected channels. This soon saved a large number of vessels.

After an intense initial effort the enemy appeared to have run out of his stock of mines, and did not lay any more until March, 1940. This left a respite of three or four months in which new counter-measures could be developed.

The Germans had begun laying magnetic mines by parachute on the night of November 21st, 1939. These were in the Thames and Humber estuaries and in Harwich harbour. On the next day a similar attack was made off Shoeburyness, and at about 10 p.m. an object was seen to fall into the tidal water. Lt.-Cdr. G. W.

Ouvry of H.M.S. *Vernon* and Dr. A. B. Wood of the Naval Mine Design Department were sent at once to investigate the object. By 3 a.m. on November 22nd the tide had fallen sufficiently to reveal the mine. It was immediately lashed down with ropes. The parachute was discovered and hauled ashore by a working party of soldiers. Non-magnetic brass tools for dismantling the mine were designed on the spur of the moment and made locally. When the tide fell on the afternoon of November 22nd, a second mine was revealed. The first, which appeared the least damaged, was stripped of its fuze, detonator, primer release and primer and hydrostatic clock. The mine and fittings were landed and sent by lorry to the Naval Mine Design Department. Here it was taken to the non-magnetic laboratory, and the rear door of the mine was removed, in the presence of many officers, without much thought of booby traps, which very fortunately proved not to be present.

A rubber-mounted dome was found, and the scientists discussed whether it contained an acoustic or magnetic mechanism, or both. Then the dome was removed, and a scale was revealed, labelled " Gauss." This showed that the mine was, at least in part, magnetic. The mechanism was removed, so that the main charge of 660 lb. of explosive could be taken away. It was studied by four scientists, who solved, within eighteen hours of receiving the mine, the chief features of its mechanism. Two of them, Messrs. W. F. B. Shaw and H. W. K. Kelly, worked through the night of November 24th in order to assist in this feat. The mechanism operated through changes in the vertical component of the earth's magnetic field due to the presence of a ship. If a magnet is set on a horizontal axis,

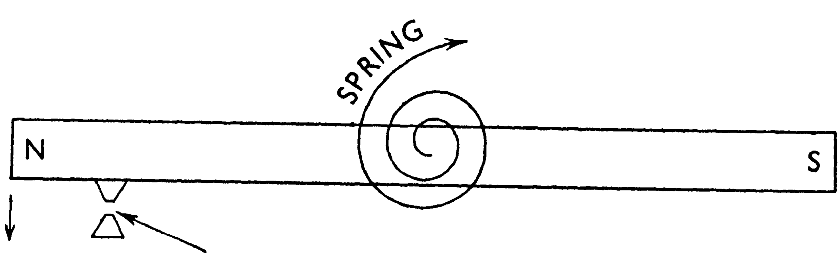


FIG. 48

like a see-saw, it will dip in the direction of the earth's magnetic field in the neighbourhood.

The German mine worked on this principle, which had been used by F. E. Smith and others in the last war. If the magnet is

fitted with a helical spring, this can be adjusted so that the vertical component of the earth's magnetic field is just balanced by the spring. The whole is slung in gimbals, so that when the mine settles on the sea-bed, the magnet settles in the correct plane. When a steel ship passes over the mine, the vertical magnetic field is increased, and the magnet's north pole is forced down. It is arranged that this shall complete a circuit to the detonator, so that the mine explodes.

By the end of the night of November 24th the scientists had discovered not only the principle of the mechanism but the strength and duration of the magnetic field required to fire it. It was immediately clear that if a ship were magnetized so that its south pole is downwards (all ordinary ships have their *north* pole downwards in the Northern Hemisphere), then it would not explode these mines, for they worked only through the downward push of a north pole. A south pole down field would merely pull the north pole of the magnet away from the contact.

These mines and their successors were full of beautiful technical tricks. They contained a pendulum which broke the firing circuit in its own mine when shaken more than half a degree by the explosion of a second mine. The Earth's magnetic field varies from place to place, so the mines were provided with a clock that automatically set the spring to the correct tension to balance the magnet in the particular latitude where the mine was laid. In the Thames estuary the mines required a certain margin of sensitiveness, so that they would not explode spontaneously. This was 0.02 gauss, or about 5 per cent of the total strength of the earth's magnetic field in that district, which is 0.42 gauss. The possible limit of sensitivity was in fact much greater.

The Counter Attack

The problem was now more precisely defined. The attack by the Mine Design Department was strengthened by the addition of academic scientists, including Dr. C. F. Goodeve and Dr. E. C. Bullard, who brought to it further perspectives, and the campaign was put under the direction of Rear-Admiral W. F. Wake Walker.

There were two lines of advance. Either you could detonate the mine by a safe means, or you could prevent the ship from actuating the mine mechanism. The first was much the better, but there was a shortage of mine-sweepers. The Prime Minister ordered that H.M.S. *Borde*, with its great magnet, the sweeper Butterworth had designed before the war, should be ready by January 1st, 1940,

It was in fact ready some days before under the command of Lt.-Cdr. R. H. Hudson, R.N., and the first enemy mine was detonated by it on Christmas Eve. The mine exploded one hundred feet in front of the ship. This success was an enormous encouragement. But the arrangement was very rough and raw. The Captain and the helmsman of the ship had to stand on sorbo rubber matting, in order to protect their legs from being broken by the shock of the explosions.

Many other methods were tried. In one suggested by a naval officer a coil was attached to a barge. In another, due to Butterworth, great coils were carried by aircraft over the mines. In yet another magnets were towed along the bottom of the ocean. (Someone even suggested that bar magnets should be attached to flat fish, which would swim near the mines and thus cause them to explode !) All of these methods suffered from the fundamental defect of making only a narrow sweep. To be satisfactory, any sweeping technique must clear a channel of practical width. Sweeping with aircraft is not very practicable because they unfortunately do not leave any mark of their track. Unlike a lawn-mower, an aircraft does not leave a track today which you can see tomorrow. The sweep must be wide enough to give a good and safe overlap between adjacent sweepings.

The first satisfactory method of sweeping was the double longitudinal or LL sweep, due to Professor B. P. Haigh, Goodeve and others. It consisted of two bouyant cables towed in parallel, through which heavy pulses of current could be discharged, so that a momentary magnetic field was produced over a large rectangular area of sea, in sufficient strength to discharge magnetic mines below it. The arrangement is shown in Fig. 49. Current is generated on the ships and used to charge accumulator batteries. It is then discharged in synchronized pulses down the cables,

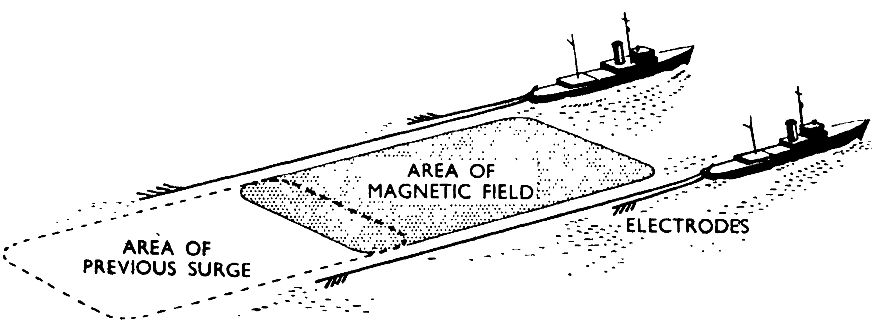


FIG. 49

completing the electrical circuit through the electrodes in the sea. Every minute a pulse of 3,000 amperes is sent through the cables for a period of five seconds. This is sufficient to explode all the magnetic mines on the sea-bottom over an area of more than ten acres. The Sweep can then be towed to the next ten acres, and quickly a wide channel can be cleared.

The first trial of the double-longitudinal sweep was made in December, 1939. The cable was made from the kind used for charging submarine batteries. Two tugs towed these cables, which were floated on logs made from wood for masts. They carried also piles of motorcar batteries. The management of the clumsy giant snakes was difficult, and one tug became marooned on a mud-bank with its cable wound around its propeller. But the sweep worked, and in the evening the Admiralty issued orders for the production of equipment and ships and the training of crews.

The log-floated cable was, however, impracticable for seamanship. It was too bulky to be stowed on the ship, and too unmanageable to be towed safely. The obvious solution was floating cable, but such was unknown. Then, one day, a Canadian sub-lieutenant remarked in the *Vernon* at lunch that floating cables were used by the dredgers on the Great Lakes, for " feeding " them. This was reported to British cable manufacturers, who replied that if the Americans could make them, so could they. The first reel of floating cable was delivered in May 1940. It was found out afterwards that the Canadian's story was a myth : the cables on the Great Lakes were not buoyant, but were floated with logs.

The buoyant cable is about three inches in diameter. It contains a hollow half-inch copper rope to carry the current. This is surrounded by foamed material to give buoyancy, and a copper sheath to dissipate heat. It is wound on large drums about 8 feet in diameter and 6 feet wide, and is paid out over the stern of the sweeper, from which the gunwale has been cut away.

It was desirable to use the smallest possible ships for the purpose. A number of special shallow draught wooden craft were built for the purpose. Such trawlers were very rarely blown up by purely magnetic mines. About 50 ships of length 126 feet were built, and 250 of length 105 feet. They resembled Yarmouth trawlers. The quarters for the crew were very restricted and must have been uncomfortable. The double-longitudinal sweep was introduced operationally in March 1940. We were very lucky to have had the few months' respite to work it out.

As sufficient mine-destroying sweeping equipment was not ready in the autumn of 1939, the less effective method of reducing

It was in fact ready some days before under the command of Lt.-Cdr. R. H. Hudson, R.N., and the first enemy mine was detonated by it on Christmas Eve. The mine exploded one hundred feet in front of the ship. This success was an enormous encouragement. But the arrangement was very rough and raw. The Captain and the helmsman of the ship had to stand on sorbo rubber matting, in order to protect their legs from being broken by the shock of the explosions.

Many other methods were tried. In one suggested by a naval officer a coil was attached to a barge. In another, due to Butterworth, great coils were carried by aircraft over the mines. In yet another magnets were towed along the bottom of the ocean. (Someone even suggested that bar magnets should be attached to flat fish, which would swim near the mines and thus cause them to explode !) All of these methods suffered from the fundamental defect of making only a narrow sweep. To be satisfactory, any sweeping technique must clear a channel of practical width. Sweeping with aircraft is not very practicable because they unfortunately do not leave any mark of their track. Unlike a lawn-mower, an aircraft does not leave a track today which you can see tomorrow. The sweep must be wide enough to give a good and safe overlap between adjacent sweepings.

The first satisfactory method of sweeping was the double longitudinal or LL sweep, due to Professor B. P. Haigh, Goodeve and others. It consisted of two bouyant cables towed in parallel, through which heavy pulses of current could be discharged, so that a momentary magnetic field was produced over a large rectangular area of sea, in sufficient strength to discharge magnetic mines below it. The arrangement is shown in Fig. 49. Current is generated on the ships and used to charge accumulator batteries. It is then discharged in synchronized pulses down the cables,

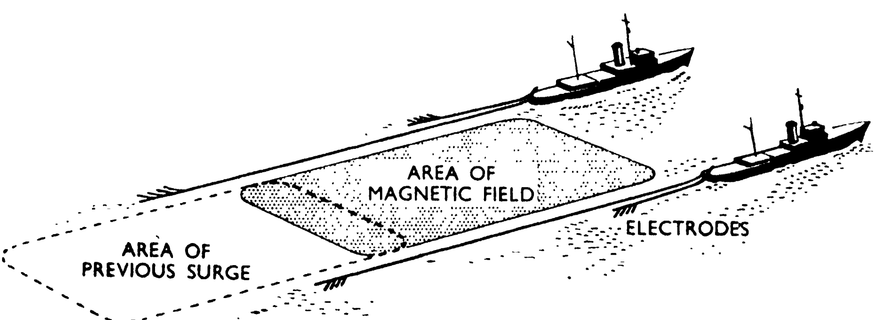


FIG. 49

completing the electrical circuit through the electrodes in the sea. Every minute a pulse of 3,000 amperes is sent through the cables for a period of five seconds. This is sufficient to explode all the magnetic mines on the sea-bottom over an area of more than ten acres. The Sweep can then be towed to the next ten acres, and quickly a wide channel can be cleared.

The first trial of the double-longitudinal sweep was made in December, 1939. The cable was made from the kind used for charging submarine batteries. Two tugs towed these cables, which were floated on logs made from wood for masts. They carried also piles of motorcar batteries. The management of the clumsy giant snakes was difficult, and one tug became marooned on a mud-bank with its cable wound around its propeller. But the sweep worked, and in the evening the Admiralty issued orders for the production of equipment and ships and the training of crews.

The log-floated cable was, however, impracticable for seamanship. It was too bulky to be stowed on the ship, and too unmanageable to be towed safely. The obvious solution was floating cable, but such was unknown. Then, one day, a Canadian sub-lieutenant remarked in the *Vernon* at lunch that floating cables were used by the dredgers on the Great Lakes, for " feeding " them. This was reported to British cable manufacturers, who replied that if the Americans could make them, so could they. The first reel of floating cable was delivered in May 1940. It was found out afterwards that the Canadian's story was a myth : the cables on the Great Lakes were not buoyant, but were floated with logs.

The buoyant cable is about three inches in diameter. It contains a hollow half-inch copper rope to carry the current. This is surrounded by foamed material to give buoyancy, and a copper sheath to dissipate heat. It is wound on large drums about 8 feet in diameter and 6 feet wide, and is paid out over the stern of the sweeper, from which the gunwale has been cut away.

It was desirable to use the smallest possible ships for the purpose. A number of special shallow draught wooden craft were built for the purpose. Such trawlers were very rarely blown up by purely magnetic mines. About 50 ships of length 126 feet were built, and 250 of length 105 feet. They resembled Yarmouth trawlers. The quarters for the crew were very restricted and must have been uncomfortable. The double-longitudinal sweep was introduced operationally in March 1940. We were very lucky to have had the few months' respite to work it out.

As sufficient mine-destroying sweeping equipment was not ready in the autumn of 1939, the less effective method of reducing

ships' magnetic field was developed. When successful, it protects the ship, but it does not destroy the mine.

Experiments were made on the design of coils for demagnetization, or de-gaussing as it was called, by winding them round ship models in the Admiralty Research Laboratory. On the basis of the results, the trawler *Sawfly* and the cruiser *Manchester*, were wound with de-gaussing coils. The methods were developed by experiments with full-sized ships ; for this was quicker, and it was much more important to secure immediately something that would work, than a perfect solution some time later. If quick results are essential, and money is no object, experiments with full-sized ships may pay.

In the crisis of the winter of 1939-1940 it was necessary not only to do something, but to let seamen see that something was being done. It was important, among other reasons, for morale. Sailors, like other practical users, like to see the answer, or a promise of an answer, in a shape that they can understand. It gives them confidence, and occasionally an excessive and touching confidence, but this is better than depression.

The first de-gaussing coils were suspended, round the hulls of the ships, with ropes. These were most unseaworthy, and the ships arrived at their ports often trailing tangles of wire astern. Then it was found that the coils would work all right if just laid on the deck. In March 1940, it was discovered, by experiments with models, that the coils would work even if laid in steel tubes inside the ship. The best level was about the water-line, but it is structurally difficult to place the cable there and not worth the trouble. One normally imagines an electro-magnet as consisting of an iron core with coils around and not inside it. Perhaps this habit of mind accounts for the slow discovery of the most convenient place for fastening the de-gaussing coil.

In the war it was more important to do a little good to a lot of ships than to seek perfect solutions. This was often done more successfully by applying simple principles on a large scale than by discovering a perfect solution for one ship, as a guide to action for the others. There were 10,000 ships in Lloyds' Register. So the procedure had to be simple and general, to be widely applied. The calculation of the size of the coil was reduced to the simple formula of 28 times the height of the ship. Huge quantities of copper cable and other material were needed for the equipment. This mobilization of material, and the training of the crews that used it, was a major aspect of the struggle against the magnetic mine. Here the work of the naval officers, Rear (later Vice) Admiral Wake Walker,

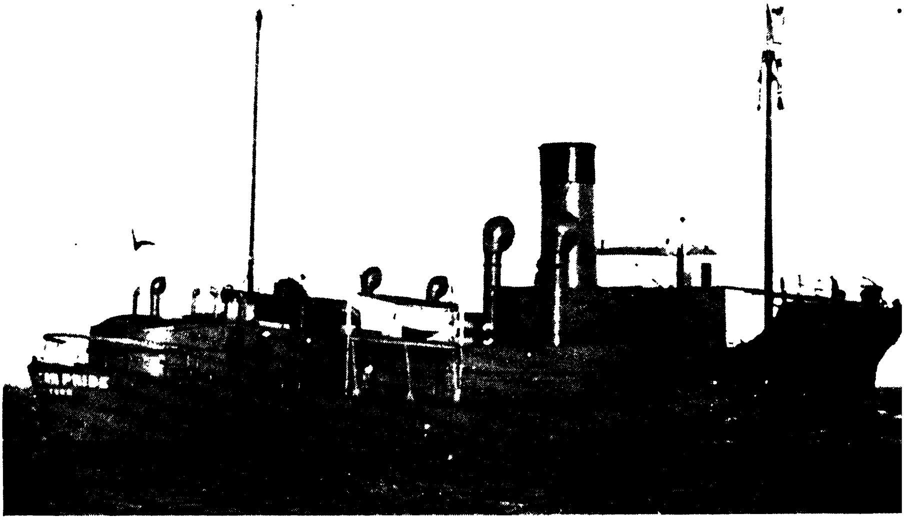
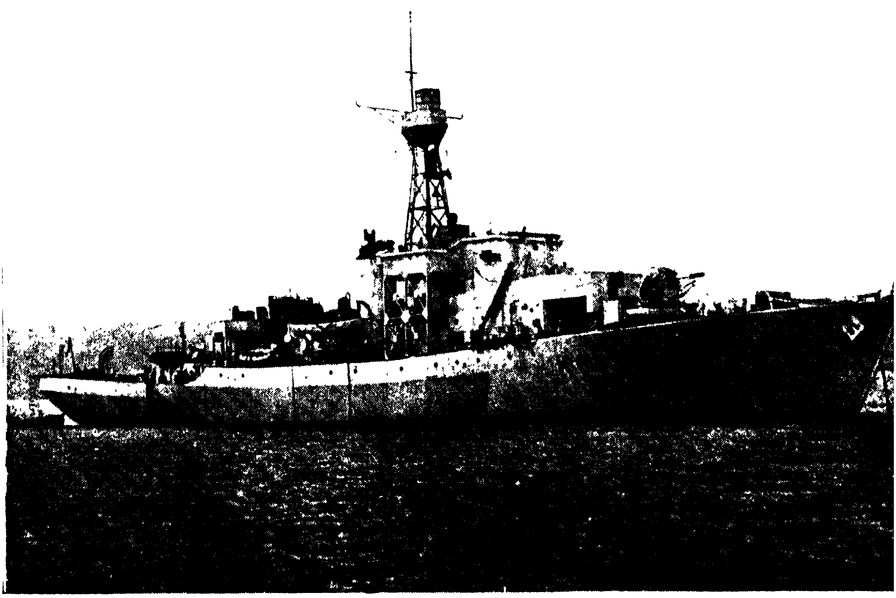
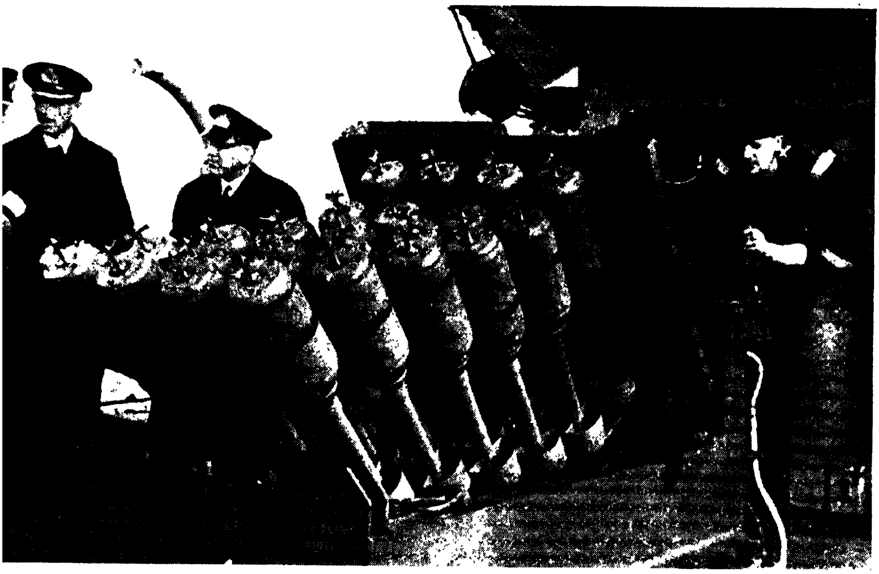


PLATE XLI

Above is the type of whaler, " Southern Pride," which suggested the lines for the design of the first corvettes. Below is a " Castle " class corvette. (*see* page 158).





A

B

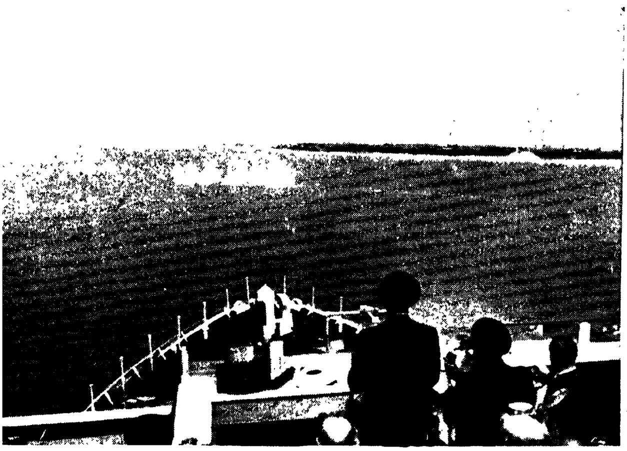


PLATE XLII

A "Hedgehog" mortar (A). It throws forward a pattern of 24 charges which land in a circle round their target (B). At (C) depth charges are exploding near a submerged U-boat whose curving track is marked by the bubbles in the smooth water behind the plumes of spray from the explosion. Photographed from the air.

C

Commander (later Capt.) O. Bellasis, R.N., and Commander (later Capt.) J. Hext Lewes, R.N., was outstanding.

Channels were arranged in the chief ports, beside which were mounted coils of 100 turns 4 to 5 feet in diameter. As the ships sailed past these coils, they immediately registered their own magnetic field. This could then be corrected to the proper value. There were about 20 of these stations in the United Kingdom and about 10 abroad. They had a staff of 100 civilians and officers, and their records were analysed in a central office. Thousands of ships were thus magnetically tested every month, and interesting new knowledge was gained. For instance, the magnetic changes that occur in a ship when it sails from the Northern to the Southern Hemisphere and back were discovered.

The natural magnetic field in a ship is fixed partly by the place and direction in which the keel is laid. From the study of the natural field in a ship, it is sometimes possible to say in which direction her keel was laid when she was built, and hence which berth in a particular yard was used.

Goodeve suggested that the ship's natural field might be neutralized by magnetizing the ship permanently in the other direction. He arranged that ships should be "wiped" with temporary horizontal coils, through which immense currents of thousands of amperes could be sent. This "wiping" technique got rid of the nuisance of permanent coils on the ships. It gave very valuable protection to a lot of ships, especially at Dunkirk. Dutch "schoots" and other small craft were taken to Poole Harbour and Portsmouth Dockyard and "wiped" by parties of men working in twenty-four-hour shifts.

This had a tremendous effect on morale. Crews who were without enthusiasm for sailing in "unwiped" ships in the morning, sailed with enthusiasm after lunch, when the ship had been "wiped." Aged mariners came up to the scientists in the street, and shook their hands for saving their lives. Confidence in "wiping" even became excessive and myths arose. One captain reported after his ship had been "wiped"; "Why, my dear chap, you could see torpedoes going in all directions harmlessly."

A most important effect of de-gaussing was that it protected the mine-sweepers. This enabled them to sweep and destroy the mines. Secondly, the enemy was forced to use more sensitive mines, which were easier to destroy. Third in importance, perhaps, was the actual protection given to naval and merchant ships.

In 1940 German magnetic mines were swept up wholesale, right through the period of evacuation of our army from the Continent. This may be the reason why the enemy began to drop sea mines on

London, Coventry, etc. By the end of May 1940, 2,000 merchant ships and 1,704 warships had been fitted.

The double-longitudinal sweep had its first operational success on February 10th, 1940. By the end of March 74 mines had been swept, and by the end of June, 287. In August the enemy began to use the acoustic mine. In spite of the temporary increase of sinkings due to this, the number of swept mines had risen to 651 by the end of September 1940.

The conquest of the magnetic mine emphasizes the importance of leadership in making use of science. Giving sound scientific advice was not enough. The scientists had to share in the execution, and show what could be done and so secure the confidence of the seamen.

As for the enemy, he persisted in using magnetic mines operating on the vertical field principle. He believed that a horizontally operated unit was less accurate than a vertical unit for exploding the mine at the right moment. If he had devoted as much effort to producing imitations of the British magnetic mine working on the horizontal field principle as he devoted to producing V2 rockets, he would probably have found the military results more profitable. But each mine of this type required about 20 lb. of copper and a good deal of nickel for relays and rods, and he decided that he could not find sufficient of these metals, though he could in fact have collected enough from sunken ships.

THE ROAD DRILL GOES TO SEA

It seemed clear in the summer of 1940 that the magnetic mine was beaten. It is now known that the enemy had come to the same opinion. He started to develop an acoustic mine, on which preliminary work had been done, in May 1940, and by a remarkable effort of development, had it ready to lay by the end of August.

Again we had no equipment ready to cope with the new weapon and again the enemy presented us with a sample at the beginning of his campaign. The German Navy had complained that the Luftwaffe had compromised the whole naval effort by dropping magnetic mines in accessible places. When the Luftwaffe repeated their mistake with the acoustic mine, the reproaches of the German Navy became particularly bitter.

The acoustic mine was invented by Wood, later Deputy Superintendent of the Admiralty Research Laboratory, in the war of 1914-1918.

The first encounter with a German acoustic mine in the recent war occurred in the Firth of Forth on August 31st, 1940, when one was exploded by a motor boat. Then the cruiser *Galatea* reported that twice in a week mines had exploded well ahead of her. Destroyers began to explode mines half a mile away. One suggest tion was that the phenomenon was due to unexploded bombs. Even at the end of September, some experts doubted the existence of acoustic mines.

The first experiments to counter the acoustic mine were made in the trawler *Harwich.* This type of trawler has a front compartment which is normally empty. The compartment was filled with water, and a road drill used to produce a powerful battering noise. In these experiments, our trawlers suffered very heavily—many being sunk as a result of damage inflicted by the mines they exploded.

On one occasion a ship was blown up when the donkey engine was started to haul in the anchor. Destroyers travelling at 20 knots were also effective exploders. There was a particular kind of coaster that was virtually self-annihilating in the presence of acoustic mines : 25 out of the 30 ships of the class were sunk by them.

Then one of the mines was secured at Cardiff, and another which had been laid in the Thames Estuary at the beginning of the daylight blitz on London. The coincidence with the blitz was an accident. The mine contained a reed tuned to vibrate on a frequency of 240 per second. The noise was picked up and communicated by the reed to a carbon microphone. The later forms

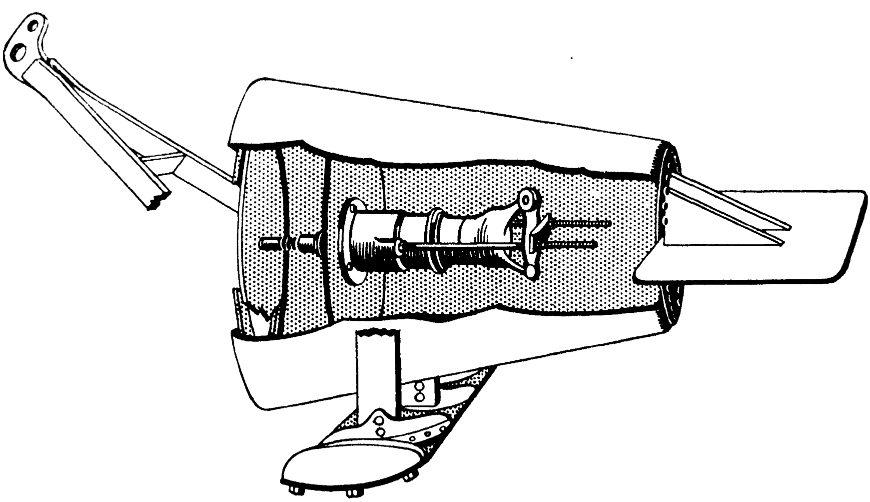


FIG. 50.—A diagram of a hammer box fitted with a " Kango " hammer.

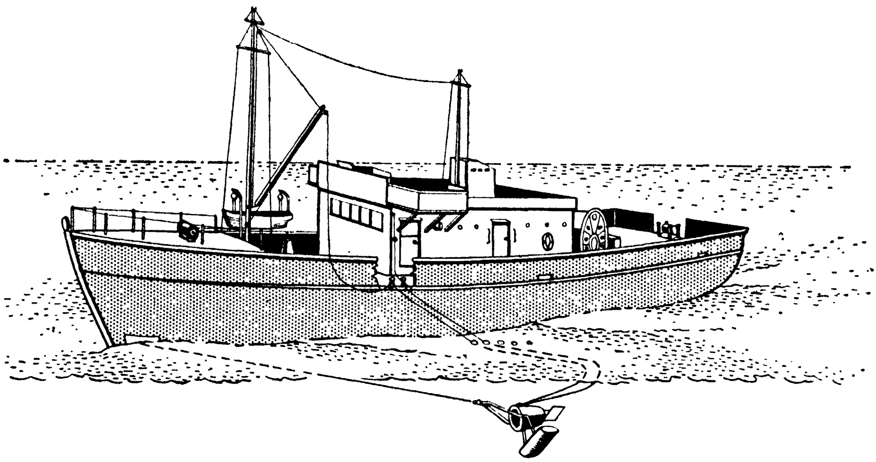


FIG. 51.—Diagram of a 105 ft. minesweeper towing a hammer box with a "Kango" hammer. The box is held away from the ship by paravanes.

of mine contained counters which operate like a telephone exchange. The mine will not go off until it is called up, so to speak, for, say, the seventh time. The first six ships will pass over it safely, and it will explode under the seventh. The mines contained clocks which could keep them disarmed for many days, until a fixed date.

In order to discover which road-drill was most suitable for the purpose of exploding the mines, a sub-lieutenant was sent to buy specimens of each that was available. The most effective was the Kango. An additional factory was built for the firm, who made it in large numbers, and were very proud of the unexpected application of their product.

Ships were given self-protection with specially large loud-speakers, or with hammers. A noise-producing box was evolved, containing a metal diaphragm about 19 inches in diameter, and $\frac{3}{8}$ inch thick, beaten by the Kango hammer. This is slung over the side of the ship, and the rattling is started beneath the surface of the sea. The chief problem was to construct a durable machine that would make a loud noise. There was not time to analyse in detail the records of all the varied noises made by ships. The sound spectrum of ships covers a wide range of frequencies, down to one cycle per second. One of the chief difficulties with pneumatic hammers was the refrigerating effect caused by the expansion of their exhaust air. A large part of the power consumption is used in neutralizing the cooling. About 100 watts, or 10 per cent of the power driving the hammer, is converted into sound-power. This hammer-box would explode acoustic mines at a distance of 1 mile. The record

distance was 5 miles. It had a conical shape in order to reduce air-space and so prevent it from floating.

For exploding mines working on very slow vibrations of the order 10 per second, a piston-displacing mechanism was used. In this the speed of the stroke was visible (and the vibration is below the minimum range of audibility, that is, 40 per second). It had an overall size of about 4 feet, and contained an 8 h.p. electric motor, which delivered rhythmic pushes, by means of a cam, to one of the ends of the chamber. The enemy did not introduce mines working on this frequency until the last month of the war, but the counter-apparatus had been evolved before then.

ANTICIPATORY RESEARCH AND ITS REWARD

By the end of 1940 it was evident that the enemy was bent on the use of non-contact mines. The immediate problem was to complete the knowledge of the magnetic properties of ships and the sounds emitted by ships.

But the future programme required decisions on scientific strategy. In view of the enemy's tendencies, what kind of mines might he introduce in future ? They might be based on further developments of the magnetic and acoustic mines, or they might be based on new principles ; for example, on water pressures. When a ship passes by, a slight decrease in pressure occurs in the water below. When it moves very near to the wall of a dock or harbour, a similar effect causes the ship to be sucked against the side. Possibly the enemy might apply this phenomenon to the operation of mines.

In 1941, a programme of fundamental research was started at the Naval Mine Design Department, mainly under the inspiration of Captain E. F. Collingwood, R.N.V.R., a Cambridge mathematician who is a member of the naval family of Collingwoods.

The de-gaussing investigations had provided a fairly complete knowledge of the magnetic fields of ships. The complete spectrum of sounds made by ships was investigated in the audible region, and in both the sub- and super-audible or sonic regions. Nine hydrophones were set up at Innellan on the Clyde for listening to passing ships. It was found that the sound-output was mainly due to propellers, and the spectrum extended from 1 vibration per second to 100,000 per second. At low frequencies the sound consisted mainly of harmonics of the frequency of the shaft. Modified quartz piezo-electric hydrophones were used to measure

vibrations as low as 1 cycle per second. High frequency vibrations were measured with tourmaline hydrophones.

Experiments were begun on the measurement of the hydrodynamic pressure under a moving ship. The pressures were measured with aneroid bellows, whose motion was in turn measured by a Shakespeare micrometer, and recorded by apparatus set up on shore. The fields of pressure were also explored with models in tanks.

As a result of this anticipatory work, we knew what to do when the enemy came forward with new mines. We were not frightened through being in ignorance. If you have no idea at all what to do, it is difficult to preserve morale, but if you have some idea, you can give confidence to yourself and others.

The outstanding achievement of anticipatory minesweeping research came at the invasion of Normandy. This presented the enemy with ideal conditions for a mining offensive. He introduced two new acoustic mines, of which one could not be swept with hammer-boxes, and the other was dangerous to them. These mines were countered with an explosive sweep which had been developed for just this purpose and kept secret until used for the first time on 6th June, 1944.

German messages ordering the laying of mines of a new but unidentified type were intercepted on June 14th. Five days after the order to lay these was given, on June 19th, specimens were secured. They were one more present from the Luftwaffe, which laid two on land in France by mistake. They weighed about a ton each, but they were shipped over within 24 hours to the Naval Mine Design Department, and were taken to pieces during the night of June 21st. The presence in their construction of a rubber bag for a pressure-unit immediately revealed that the enemy was using an entirely new type of non-contact mine, which had been held secret by the German High Command and only used in the crisis attending the Allied invasion of the Continent.

In the morning of June 22nd the sensitivity of the units was measured, using techniques evolved during the British development of pressure mines. In the afternoon of this day, a meeting was called at the Admiralty to discuss what should be done. Mr. A. T. Pickles, the Senior Scientist of the Mine-sweeping Division of the Naval Mine Design Department, arrived at the meeting with proposals for tactics already worked out during the last three years. They had found that if the speeds of ships of specific size were below a certain value, the suction effect would not be sufficient to activate the mines. These speeds had been calculated and set

out in a table, on the assumption that the mines would require a pressure decrease equivalent to six inches of water to detonate them. During the meeting, data from the examination of the mines was brought in. It appeared that they worked on a pressure change equivalent to one inch of water. The scientists thereupon divided all their speeds by 2½, which is roughly equal to the square root of 6, for the pressure variation at depth is proportional to the square of the speed of the ship.

In the evening the Chief of Naval Staff was able, on the scientific advice given to him, to issue the following historic signal :—

" From : Admiralty.

A new unit has been introduced to type 'C' and 'G' mines. This unit renders the mine unsweepable at present. A measure of security will be achieved by proceeding at a very low speed in water under 15 fathoms.

It is probable that the mine has considerable limitations and investigation is proceeding. Further signal follows.

From : Admiralty.

The following speed limitations are expected to provide safety to ships operating in areas where the mine units referred to in Admiralty's 221653 are likely to exist.

5-10 fathoms :

All ships larger than destroyers and minesweepers 4 knots. Destroyers and Fleet sweepers 8 knots. Smaller craft no restrictions.

10-15 fathoms :

Over 15,000 tons 6 knots. Medium ships 8 knots. Destroyers and Fleet sweepers 12 knots. Smaller craft no restrictions.

15-20 fathoms :

Over 15,000 tons 6 knots. Medium ships 10 knots. Destroyers and Fleet sweepers 15 knots. Smaller craft no restrictions.

20-25 fathoms :

Vessels over 15,000 tons are advised to proceed at moderate speed. Other vessels no restrictions.

Self protection should not be used.

The mine mechanism consisted of a rubber air bag with an aluminium diaphragm. With a change of pressure air escapes from the bag, the diaphragm is moved, and after a time closes an electrical detonating circuit. A change of about 1/1,000th in the total pressure, equivalent to that of about ½ inch of water, exerted for about six seconds, was needed to operate the mechanism. This device, called an "oyster," is shown in Plate XLV. The long period of actuation was designed to avoid operation by swell (which rarely produces suctions lasting longer than 5 seconds in sheltered

waters) and to making sweeping difficult. A medium-sized ship steaming at 8 knots will exert the suction effect for 20 seconds.

We had no sweeping equipment for simulating this time effect, so dependence on reduction of speed was advised. It happened that the Seine Bay was so full of ships that manoeuvring at high speed was sometimes impracticable. The reduction of speed below the advised limit consequently had less effect on the efficiency of operations than might have been expected.

The anticipatory work made the enemy's mining campaign during the invasion an almost complete failure.

Another important success was gained against the acoustic homing torpedo. The German command had promised U-boat crews that this would regain for them command of the Atlantic. Within three months of its introduction we had produced a counter-measure. The U-boat captains knew that it existed, but did not know what it was. This had a bad effect on their morale, and the use of this torpedo was dropped. Finally, we succeeded in sweeping the Scheldt Estuary. It has been said that " if we had known what was there we should almost have despaired." But all of the sweeping methods were pushed as far as they would go, and brought unexpected success. If you sweep hard enough, even with rough tools, you do achieve success.

These experiences show the value of numerous rough full-scale experiments. They sometimes give results which cannot be achieved by the most brilliant theoretical and laboratory researches on models or by single full-scale experiments.

UNDER-WATER EXPLOSIONS

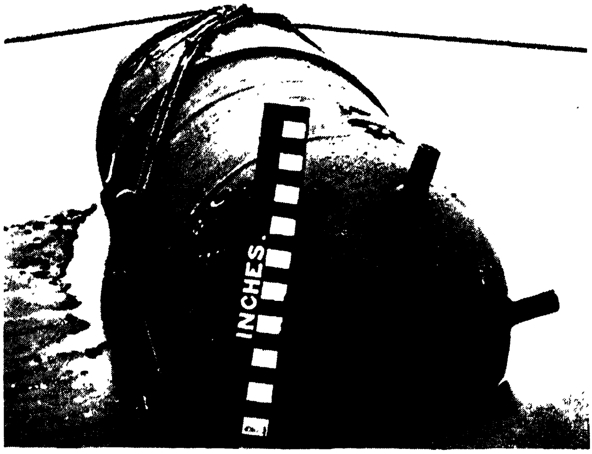
The way that science is used in war is determined by the nature of military conceptions. Warfare is primarily an offensive activity. People rarely defend things just for the fun of it, they do not provoke attacks for the pleasure of indulging in defence.

The priority of the offensive in military psychology has led in the past to concentration on the invention and development of weapons for damaging the enemy, rather than on the development of defensive technique. This has been widely reflected in past naval policy. Immense sums have been spent on discovering how to sink ships ; perhaps ten times as much as on defensive measures. It is now necessary to make an equal effort to discover how to keep ships afloat.

During the recent war there has been a great advance in the destructiveness of explosives and of under-water weapons. The

PLATE XLIII

The first magnetic mine to be recovered. (*see* page 162.)



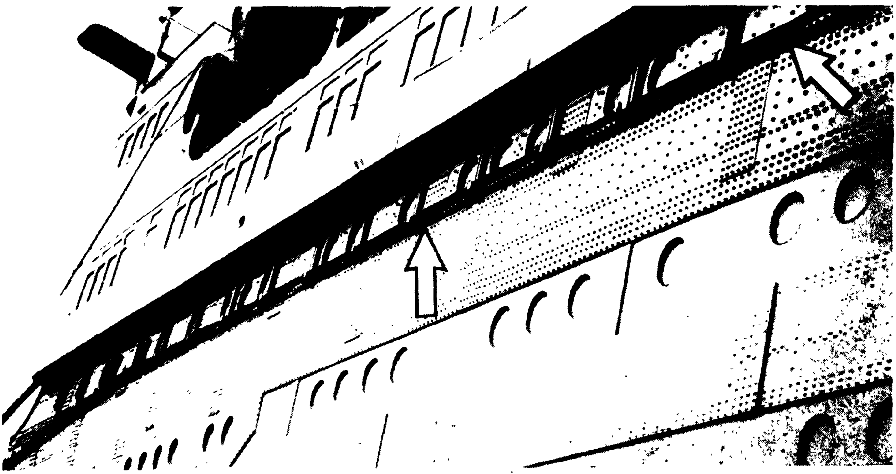


PLATE XLIV

The de-gaussing cable running along the side of the liner Queen Elizabeth to protect her against magnetic mines. (*see* page 170.)

PLATE XLV

A mine with an "oyster" attachment, which is contained in the dome-shaped cover shown in the bottom right-hand corner of the photograph. (*see* page 177.)

PLATE XLVI

As a projectile moves through the water, its nose may produce a turbulent hollow in the water. Suitable shaping of the nose greatly reduces this disturbing effect and may double the rate at which depth-charges sink towards U-boats at which they may be fired.

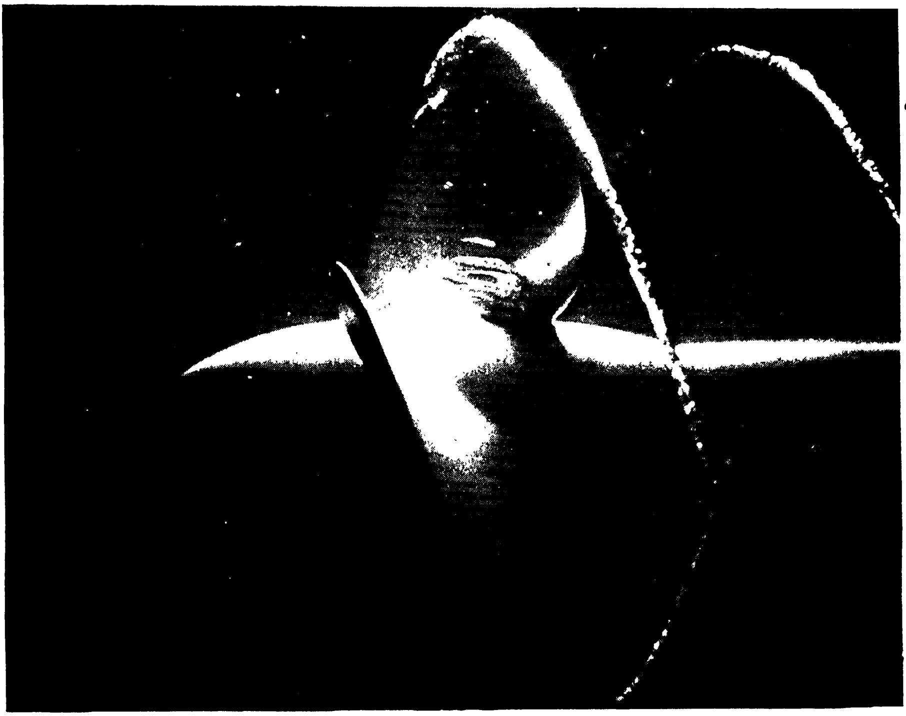
The hollow formed by a sphere one inch in diameter which has been shot into water at a sharp angle.

This picture is of the underside of the hollow shown above and has been secured by photographing through a mirror.

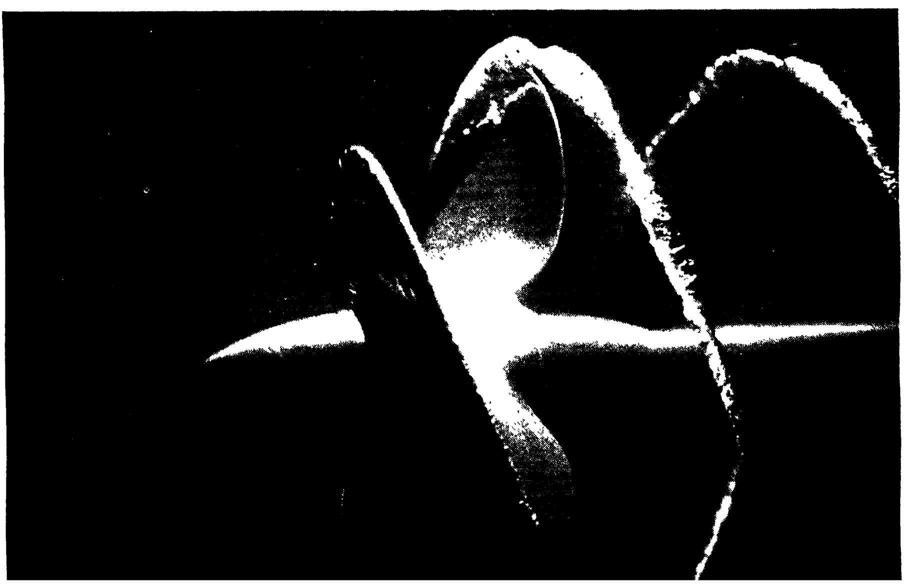
This illustration, a photograph of a model projectile shot through a tank of still water at the Admiralty Research Laboratory, shows turbulent cavitation at the nose of the model.

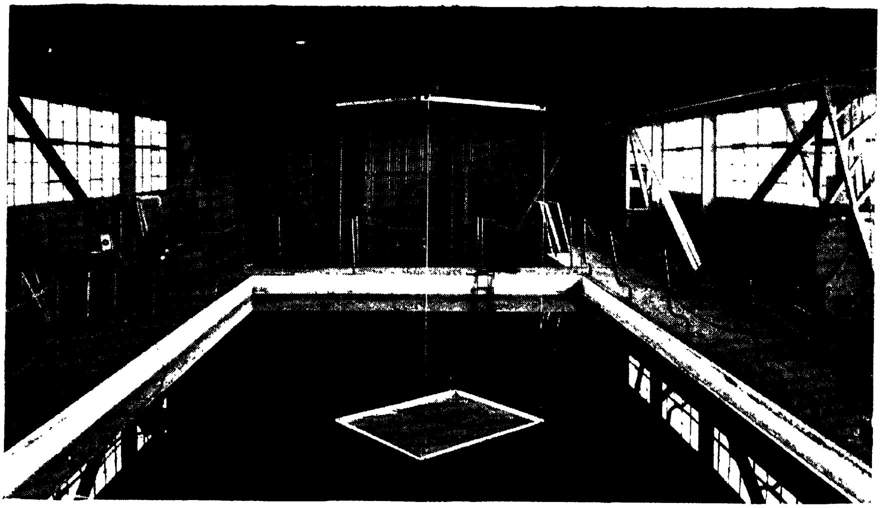
PLATE XLVII

Photograph of a propeller taken in 1/40,000th of a second. The formation of hollows in the water behind one of the blades is shown. This is a bad case of the phenomenon of cavitation. The rushing-back of the water into the hollows produces a hammering on the propeller, leading to pitting of its surface.

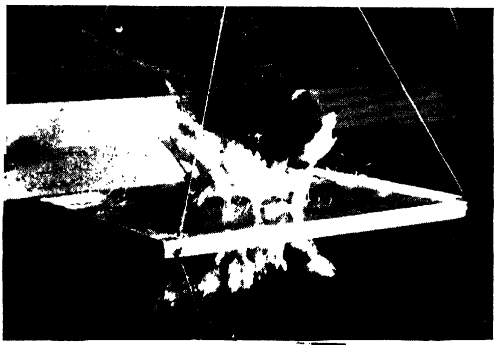


As a result of experiments the shape of the propeller has been improved and cavitation has disappeared.



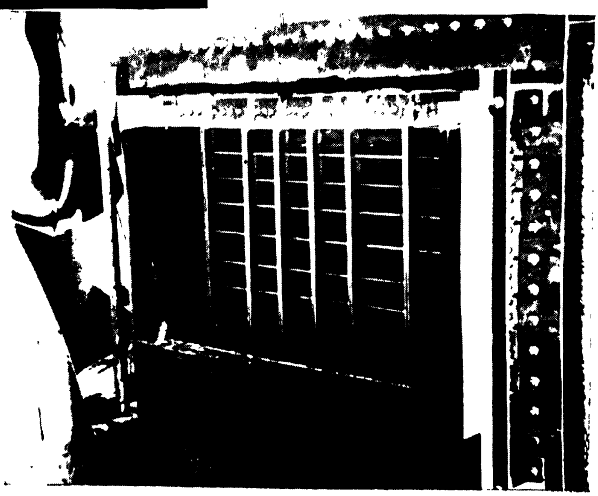


A metal plate or tray held on the surface of the water in the large experimental tank at the Naval Construction Research Establishment at Rosyth. Small charges are exploded in various positions to forecast the effect of a large charge placed in a similar position in regard to the side of a ship.

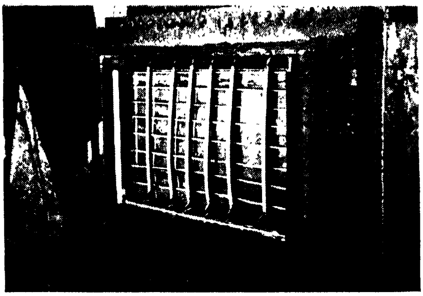


A flash photograph of an explosion of a small charge under a plate. By a series of experiments, it is possible to determine factors which enable large-scale effects to be calculated from small-scale experiments.

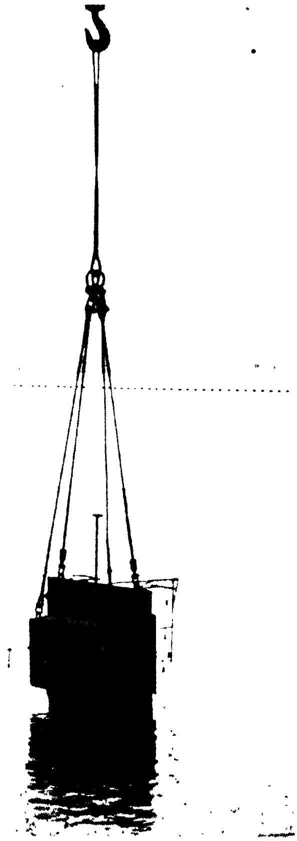
In the experiment shown, where a small charge has been photographed in one-millionth of a second, the smoke from the combustion of the explosive is seen clearly separated from the spray.



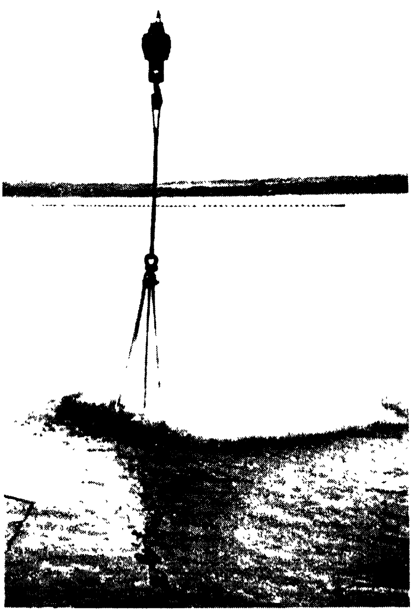
A model of part of the structure of a ship fixed in the side of a tank. A charge is exploded inside the water in the tank, while one side of the structure is exposed to the air, thus simulating the conditions when a charge is exploded in the water outside the hull of a ship.



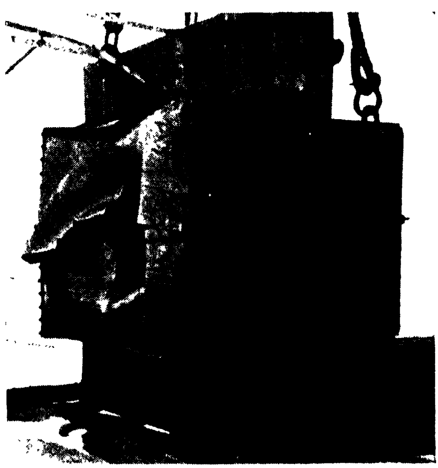
The structure distorted after the charge has been detonated.



A large metal target being lowered into the water in the harbour, where charges can be used that are beyond the size which can be safely fired in an experimental tank.



The model has been sunk below the surface and the charge has just been fired.



The model has been raised in order to study the effects of the explosion.

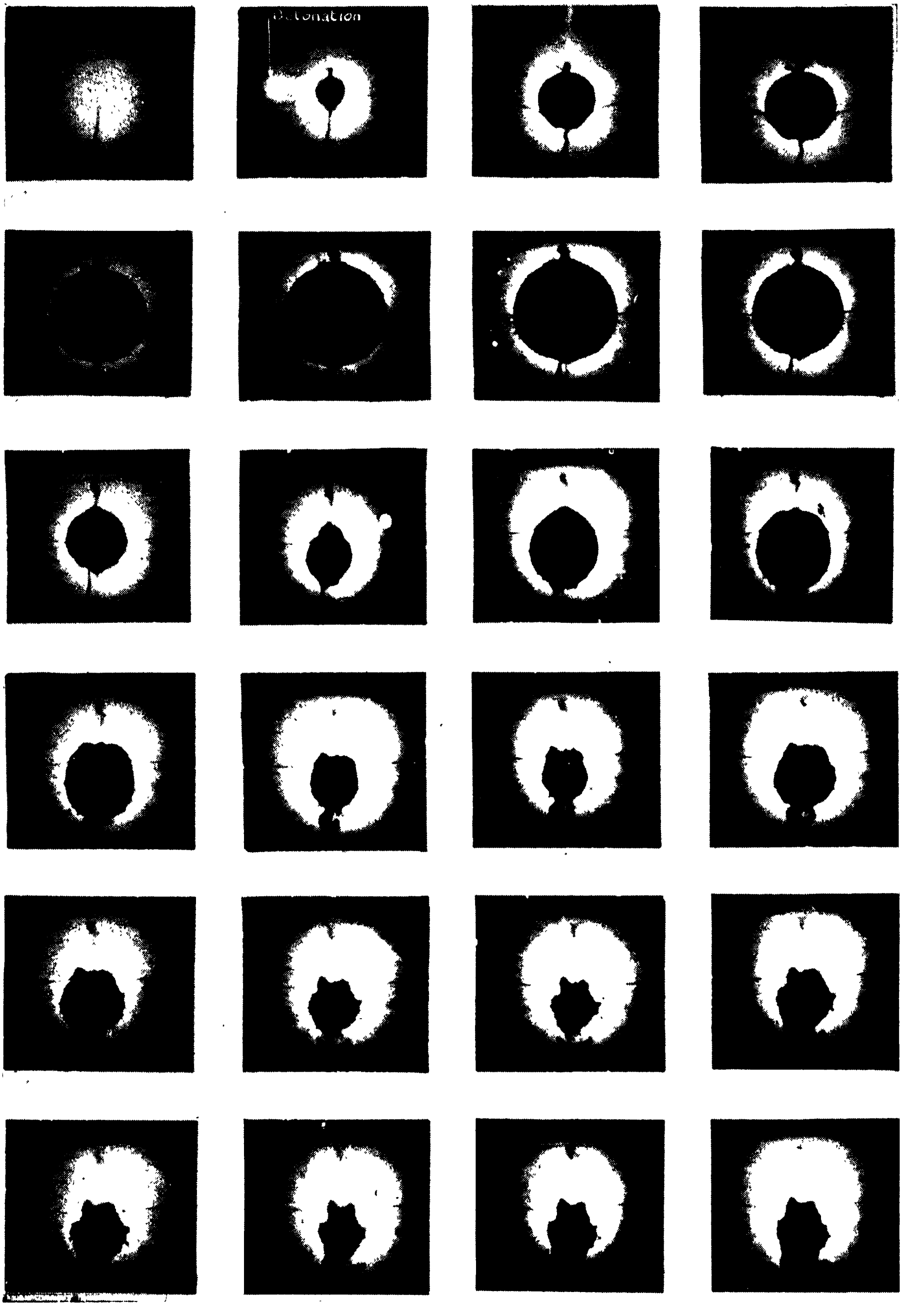


PLATE XLIX

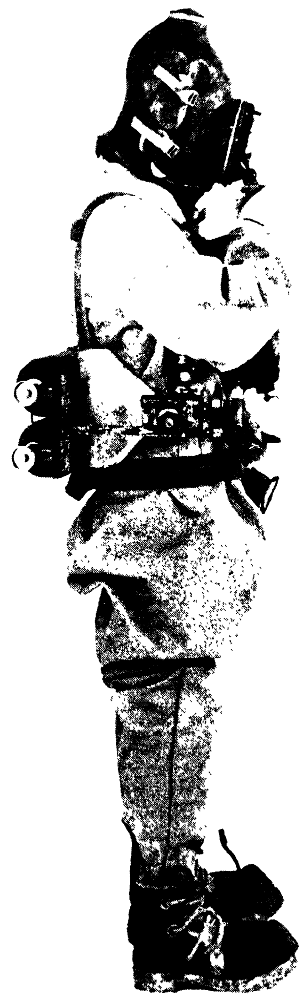
A sequence of photographs of what happened when 15 grains of an explosive were detonated under water. The sequence shows the oscillatory increase and decrease in the size of the bubble of gas from the explosion. The time interval between the first four pictures is $\frac{1}{750}$ second, and between subsequent pictures $\frac{1}{250}$ second.

PLATE L

The " frog-men."

A. An underwater swimming suit with Dunlop underwater swimming-breathing apparatus, and fins. Pure oxygen is supplied, and the duration for one underwater-swim is up to 90 minutes.

A



B

B. A suit for divers engaged in the recovery of mines. The gas supply is a mixture of 45 per cent oxygen and 55 per cent nitrogen. It can be used safely to a considerable depth.

PLATE LI

The " Sladen " breathing apparatus and dress developed for " human torpedoes." Pure oxygen can be supplied for a period of up to six or seven hours. This oxygen apparatus probably gives longer endurance than any other kind in existence.

variety and intensity of the attacks to which modern warships may be subjected, quite apart from the atomic bomb, are overwhelming compared with those of twenty-five years ago.

It is therefore necessary to elucidate exactly how and why ships are sunk, in order to see how they can be improved, besides gaining yet further knowledge on how to destroy them.

To meet the need for deeper scientific knowledge of these problems the Admiralty initiated in January 1943, the " Undex Works " at Rosyth now known as the Naval Construction Research Establishment (N.C.R.E.). Its primary aims were :—

(1) to discover how to make warships more resistant to underwater explosions ;
(2) to discover how to make the best use of under-water explosives in attack.

This establishment is a combination of laboratory and works set in the naval dockyard at Rosyth, near the Forth Bridge. It is in immediate touch with the Navy, and one may see moored nearby H.M. ships of all sizes and types such as capital ships, aircraft carriers, cruisers, etc.

The closest collaboration with the users of the ships is necessary because a ship is very complicated. It has many features, and its value depends on the combination of all. The only way to save a ship is to make it the best ship in every way. This involves combinations of hitting power, speed, the discovery and use of the most suitable metals, improvement of joints, and many other aspects.

Quite small changes in one item can have a great effect on the ship as a whole. For instance, in one battleship design if the ship's boats had been increased in length from 45 feet to 55 feet, the total increase in the weight would have been about 2,000 tons. The deck space was fully occupied and therefore the only way to accommodate the longer boats would have been by increasing the length of the ship herself by about 10 feet. Thus 10 feet more hull structure, side armour and deck armour, would have been required, and this increase in size and weight would have called for more powerful and therefore bigger and heavier engines to develop the same speed. Thus a sort of vicious circle would have been started, so that adding boats whose total increased weight was only a ton or so would have increased the ship's displacement by about 2,000 tons.

Although the above example is an extreme case, it is easily seen that if you can save about 10 tons on a fitting you may save, say, 50 tons in the ship as a whole. The importance of metallurgical research in this connection is evident.

The study of the strength of materials is equally important. In the past, engineering science has been based on the behaviour of metals in their elastic range. It has been generally assumed that a structure under stress should be designed so that it should bend or stretch but return to its original shape after stress. This is necessary in bridges and machines of many kinds, but not so in withstanding explosions. In general, a ship has to withstand only one or a few explosions; after that it goes to a dockyard for repairs. It is not like an engine which has to recover completely from hundreds of rhythmical stresses every minute. Thus it does not matter so much if it is pushed out of shape by an under-water explosion, as long as it does not break. The intentional design of metal structures to deform, and not to recover, under stresses is a relatively new branch of applied science. It deals with metals as plastic, not as elastic materials. Much is yet to be discovered about the most skilful use of metals in their plastic range.

The break-down of metals under explosion is a plastic phenomenon. N.C.R.E. is investigating it by laboratory, medium and full-scale experiments. They use Arditron cameras, which give a flash with a duration of one-millionth of a second, to photograph what actually happens when a hole is blown through a metal plate with a small charge. They have secured very clearly defined pictures at intervals of 1/500th of a second of the progress of such an explosion. The debris moves at 2,000 feet per second or over 1,200 miles an hour. The phenomena are remarkably similar in general features to those of full-scale explosions with operational charges.

Experiments with small charges of 1 oz. to 8 oz. are made in a water tank 40 feet long by 20 feet wide and 11 feet deep. Floating metal trays and models are placed on the water, and the small charges are exploded underneath. The top side of the tray is open to the air. The arrangement is thus analogous to that inside a ship which is being attacked under water, for the charge explodes in the water, by the ship's side, while its effects are felt on the inside of the ship, which is exposed to air. A metal observation tower with a strong glass window can be lowered into the tank, so that underwater explosions may be observed directly.

Besides small-scale work in laboratory tanks, experiments on a larger scale are made by lowering larger plates and specially made structures, resembling portions of bulkheads, or other parts of ships, into the harbour. Larger explosive charges can be used, and their effects registered by electrical recording on the harbour-side. It is found that when metal breaks under explosion the grain of the fracture points like an arrow to the position at which the fracture

originates. The fact is as yet unexplained but is very useful in interpreting results.

The Rosyth seagulls are interested in these experiments. Each explosion stuns many fish, and the birds dive in scores to pick them out of the water. These explosions attract the birds instead of scaring them away !

Another method of investigation is to detonate explosives inside a large strong metal tank about 10 feet square, full of water. On one side of the tank there is a large hole, across which plates of various kinds can be fastened. The observer in the air outside the tank is in an analogous position to an observer inside a ship that is being attacked. A large number of tests on the strength of welded joints have been made in this way.

Fundamental research to give exact information on how the elementary metal shapes behave is being pursued. The ends of strong cylinders are closed with circular plates, and the air-filled structure is then sunk in water. Charges are exploded in the water, and the effects on the plates minutely studied. In another series of experiments, a metal cylinder is filled with water, and surrounded by an air jacket. A charge is then detonated in the water on the middle of the axis of the cylinder. In this way the behaviour of circular plates and cylinders is being investigated, as a step toward the analysis of what happens in the complicated structures of ships. The experimenters try to imitate actual cases of damage that have occurred to ships in action, and analyse the causes.

The N.C.R.E. and others in the Admiralty investigate the damage caused to fittings, for example in a submarine, by under-water explosions. The structure as a whole may resist the shock, but the electrical fittings, engines, etc., may be damaged. These may require special designing for protection against shock. The engines may be clamped on rubber buffers, or on C-shaped springs which collapse in their plastic range when severely shocked.

N.C.R.E.'s resources for using explosives have enabled them to contribute towards the improvement of explosives. For example, when the mixture of aluminium powder for improving the performance of explosives was first introduced, a very finely-powdered variety was used. The manufacture of this fine powder in sufficient quantity was very difficult. N.C.R.E. showed, however, that the use of relatively coarse aluminium grist would not lead to inefficiency in the explosive and thus eased the problem of production.

The Bubble Effect

It has been observed that charges exploding underneath ships and submarines are often much more destructive than explosions of similar charges in the water at the side of or above them.

On one occasion, a 250-lb. bomb dropped from one of our aircraft fell on the bridge of one of our submarines. The submarine had begun to dive, and when it reached the depth at which the bomb had been set to detonate the bomb exploded. The submarine lost only the periscope and parts of the conning tower, etc. If the bomb had exploded as close under the submarine, the vessel undoubtedly would have been lost. Submarine captains have in general reported that depth charges are most dangerous when they explode underneath the vessel.

In shallow water, there is strong reflection of the blast from the sea-bed, which adds to the blow from below. But this explanation does not hold in deep water.

The lead in the explanation of this phenomenon has been given by Sir Geoffrey Taylor, the eminent physicist and member of the scientific advisory panel to N.C.R.E.

The shock-wave from an underwater explosion is the same, whether the charge explodes above or below the ship. Why, then, should the effects in the two cases be different ? The explanation rests on the fact that when the charge explodes in the water it forms an extremely hot bubble of gas, which expands at a tremendous rate. Consequently, the water is pushed away and acquires a high momentum. It continues to move outwards after the gas has expanded to the degree at which it is in equilibrium with the pressure in the water before the explosion. Thus the gas bubble expands beyond its equilibrium position and presently begins to recede again. The water walls of the bubble now begin to move inwards and rush towards each other with enormous speed compressing the approximately spherical bubble of gas back again into a small bubble. Then there is a sudden reversal, and the bubble once more begins to expand a second time with explosive violence. A second shock wave is then sent out. It is not so strong as the first, but when suitably placed, is able to do much damage. It was subsequently found that this explanation was also inherent in some mathematical calculations on underwater explosions made many years before the war by Butterworth, then serving at the Admiralty Research Laboratory, who showed that an underwater explosion under suitable conditions is not a single " bang," as might be imagined, but a rapid succession of " bangs " of diminishing intensity.

The bubble is really an oscillating system, whose movement is relatively slow at the stage of full expansion and very fast at the stage of maximum contraction. Three or more expansions and contractions may occur, sending out three or more shock-waves, in decreasing order of strength.

Consider, now, what happens when a charge explodes above a submarine. The bubble proceeds through its oscillatory expansions and contractions, but it also rises through the water, since it is a gas and lighter than water. The second and third shock-waves will occur farther and farther away besides being weaker and weaker. Thus they will do no harm.

But what would happen if the charge exploded underneath the submarine? The bubble would rise, and the second and third shocks from expansion might be much nearer, or actually on the hull. In that case, though the shocks were intrinsically weaker, they would be in a position to do much more damage.

A second effect also emphasizes this tendency. The oscillating bubble of gas moving in water tends to be sucked towards any nearby rigid body. This is due to the same cause as the fall in pressure which occurs underneath a ship passing through a shallow channel, or when two ships sail very close to each other ; it is a characteristic of the movement of fluids. Hence a bubble from a charge which explodes in the water near the side of a ship tends to move towards the side, or, if it is near the bottom, towards the bottom. Thus this effect, also, tends to bring the bubble nearer the submarine or ship, and to enable the secondary and tertiary expansions to exert their destructive effect.

The analysis of the bubble effect suggests a method of minimizing the effect of underwater explosions by substituting yielding for over-rigid ship sides. If the side began to yield, the suction effect would be reduced and the bubble would not be pulled by it towards the ship or submarine.

WAR DIVERS AND SWIMMING SABOTEURS

Late in 1941, the Italians introduced belligerent divers, who piloted torpedoes under water against our ships. They used a diving suit supplied with oxygen, which enabled them to remain under water for a considerable period. Some of these were captured, and in February 1942, the Admiralty started research on this and associated problems of self-contained diving equipment, with the assistance of Professor J. B. S. Haldane and others. The group was set the task of producing within four months equipment which would enable men to pilot human torpedoes, operate, or work from, midget submarines, and remain under water on oxygen for longer periods than had ever been achieved before.

In the course of the research it was found that the dangers of oxygen poisoning were much greater than had previously been

believed. In addition to respiratory problems, the effects of cold and heat, and of the blast from explosive charges, were investigated. The latter experiments were made with 50 seamen who volunteered for the work. It was shown that small charges were harmless unless surprisingly close.

Early in 1943 the group was asked to produce an under-water swimming suit. The chief problem was the evolution of a sufficiently supple close-fitting suit, which would not impede the diver, but which would protect him against the coldness of the water. With the assistance of rubber manufacturers experienced in the manufacture of flying suits the group produced in a few weeks an under-water swimming suit, with swimming fins, and other accessories.

These suits were worn by swimming saboteurs for attacking closely-guarded and difficult special targets. Very large numbers of them were used on D-day, and saved many casualties amongst landing craft in the first assault wave.

Special suits for divers examining mines were also required. They were to be non-magnetic, and there were not to be more than two men working on the mine at once. The depth at which the suits were to be worn was too great for the use of pure oxygen, so it was decided to use oxygen-nitrogen mixtures. These were worked out by Haldane and Surgeon Lt. Cdr. K. W. Donald, R.N., for any required depth. A suit was developed for use down to 120 feet of water. It was possible to come to the surface quickly from this depth without the stops usually necessary to prevent the pains due to divers' " bends."

Many mines were successfully recovered or rendered safe with the aid of this suit. From this suit a new type was developed, consisting of a fully flexible and mobile dress and apparatus employing oxygen-nitrogen mixtures in which long spells of hard work and rapid movement were possible in depths down to 55 feet, without fear of oxygen poisoning. This type of suit was used on a large scale in 1944-45 for searching captured ports and harbours and clearing away the enemy booby traps and mines. It was an essential contribution to the organization of supplies for the advancing armies.

The big increase in the amount of self-contained diving on operations revealed new problems. The most serious of these was " shallow water black-out." The diver became unconscious in depths at which oxygen poisoning and other known troubles do not occur. It was found that the effect was due to excessive accumulations of carbon dioxide in breathing sets which appeared to be

correctly designed by accepted standards, and this has led to a new extension of fundamental research.

Such have been some of the physiological investigations which made possible the human torpedo attacks on the Italian fleet, the damaging of the *Tirpitz* by midget submarines, the clearance of obstructions from the path of the invasion forces on D-day, the clearing of the captured ports. The latest problem to be tackled is how to see through mud, for the aid of salvage divers. The research group are confident of success.

Among the scientists who have been especially prominent in the work of the Admiralty's Experimental Diving Organization is Donald, under whose technical advice and guidance, and in whose presence, every experiment has been carried out. Besides collaborating with other Admiralty establishments, much work was done in the laboratories of Siebe Gorman and Company, Ltd., and the Dunlop Rubber Company, Ltd.

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